Replication: Performance of Cellular Networks on the Wheels

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Abstract

In 2022, 3 years after the initial 5G rollout, through a cross-country US driving trip (from Los Angeles to Boston), the authors of [28] conducted an in-depth measurement study of user-perceived experience (network coverage, performance, and QoE of a set of major 5G "killer" apps) over all three major US carriers. The study revealed disappointingly low 5G coverage and suboptimal network performance – falling short of the expectations needed to support the new generation of 5G "killer apps. Now, five years into the 5G era, widely considered its midlife, 5G networks are expected to deliver stable and mature performance. In this work, we replicate the 2022 study along the same coast-to-coast route, evaluating the current state of cellular coverage and network and application performance across all three major US operators. While we observe a substantial increase in 5G coverage and a corresponding boost in network performance, two out of three operators still exhibit less than 50% 5G coverage along the driving route even five years after the initial 5G rollout. We expand the scope of the previous work by analyzing key lower-layer KPIs that directly influence the network performance. Finally, we introduce a head-to-head comparison with Starlink's LEO satellite network to assess whether emerging non-terrestrial networks (NTNs) can complement the terrestrial cellular infrastructure in the next generation of wireless connectivity.

CCS Concepts

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

Keywords

5G, Measurement, Coverage, Network Performance

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1 Introduction

5G networks with ultra-high bandwidth and ultra-low latency are expected to enable an emerging class of mobile applications such as Augmented and Virtual Reality (AR/VR) [39, 40, 43, 47, 48], Connected Autonomous Vehicles (CAVs) [59, 62, 69], and the Metaverse. Many of these applications have practical significance in driving scenarios, where maintaining high QoE is essential.

In 2022, 3 years after the initial 5G rollout, Ghoshal et. al [28] conducted a cross-country drive (from Los Angeles to Boston, 5700+ km) in the US, measuring cellular network coverage, network performance, and the QoE of a set of major 5G "killer" apps (cloud-assisted AR, CAVs, 360^o video streaming, and mobile cloud gaming) over all three major US operators. Their goal was to present a holistic view of operational 5G networks in driving scenarios, capturing the real world network capabilities over a broad geographic footprint. Their findings revealed disappointingly low 5G coverage while driving for all three operators – with two of them having less than 25% 5G coverage along the driving route. More critically, their study showed extremely poor network and application performance even in areas with full 5G coverage.

5G deployment has advanced significantly since the 2022 study. Operators are transitioning from Non-Standalone (NSA) to Standalone (SA) 5G, introducing features like higher carrier aggregation (CA) and new frequency bands with diverse duplexing modes – all aimed at improving performance. At the same time, the wireless landscape is evolving with the rise of non-terrestrial networks (NTNs). In particular, Low-Earth-Orbit (LEO) satellite networks are transforming global connectivity by offering Internet access in remote or underserved areas where traditional networks fall short. These changes in the wireless ecosystem necessitate a new large-scale measurement study to reassess the current state of cellular coverage and performance while users are on the move, and to compare it against the state established by the previous study back in 2022.

Numerous studies [9–11, 13, 15, 17, 20, 21, 37, 51, 60, 61, 66, 67] have evaluated various 5G aspects after the Ghoshal et al. study was performed. However, most are limited in geographic scope, focusing on one [11, 51, 66] or a few cities [15, 17, 18, 21, 60, 61, 66].

A few studies use large datasets collected via driving measurement campaigns [7, 13, 31, 67], but each of them focuses on a specific 5G aspect, e.g., handovers [31], or multi-carrier access [13], and none of them tracks performance evolution over time. Some works study the evolution of 5G over extended time periods using crowdsourced datasets [9, 37, 65]. While these datasets offer broader geographic and user coverage compared to cross-country drives, they do not capture user mobility or lower layer features, they do not obtain measurements over different networks at the same location and time, and they do not analyze application performance.

In this work, we bridge the gap by replicating the study by Ghoshal et. al in [28] (target paper) driving along the same route from Los Angeles to Boston, while simultaneously measuring the coverage and performance of all three major US operators. Additionally, we expand the work on two fronts: (a) by exploring the impact of different lower layer features such as CA, bandwidth configurations, and MIMO on the network performance, and (b) by conducting simultaneous measurements with Starlink and performing a head-to-head comparison with cellular networks. They key findings of our work are as follows:

- All three operators have significantly expanded their 5G coverage in 2024, with two operators heavily deploying high-speed 5G (5G-mid or 5G-mmWave) and extending it beyond urban centers. However, two out of three operators still exhibit less than 50% 5G coverage along the driving route even five years after the initial 5G rollout.
- The effect of improved coverage is clearly visible in the network performance with a dramatic improvement in throughput from 2022 to 2024 for all three operators. On the other hand, the RTT remained roughly unchanged for two operators and improved by less than 15% in the median case for the third operator, suggesting that latency remains a more complex challenge than throughput.
- Over the past two years, all three operators significantly expanded their 5G-mid downlink (DL) CA levels and aggregate bandwidth, with T-Mobile and AT&T also increasing their uplink (UL) bandwidth. The expansion is more limited in the 5G-low bands, where only T-Mobile introduced CA in 2024. In 5G-mmWave, we observe increased CA levels with Verizon in the UL direction, enabled by the capabilities of newer UE models, but, surprisingly, a drop in CA levels in the DL direction. Furthermore, we see a sharp decline in MIMO capabilities, with all three operators significantly reducing the number of 4x4 MIMO 5G base stations (gNBs) in 2024.
- The total number of handovers (HOs) per mile increased substantially in 2024 compared to 2022. On the other hand, with the exception of 5G→LTE HOs in T-Mobile's 5G SA deployments, the HO duration either remained the same or reduced in 2024.
- Our head-to-head comparison of cellular networks against Starlink shows that Starlink's network availability along the driving route was 98% (vs. 100% for the cellular networks). Interestingly, its RTT is the lowest among the four networks and its median DL throughput is commensurate to that of cellular networks. On the other hand, its peak DL throughput and its median UL throughput are significantly lower than those of cellular networks.
- Our replication of the mobile app study from the target paper for two 5G "killer" apps using a different methodology confirmed the main finding of the target paper: cellular networks were not able to support those apps in 2022. The improved 5G-mid coverage and network performance in 2024 results in a large QoE improvement for these two apps, however, fallbacks to 5G-low/LTE still hurt the performance. Importantly, application-level optimizations developed in the pre-5G era, such as frame compression and local tracking, remain relevant even in 2024, despite the drastic improvements in cellular performance. Despite its lower RTT compared to cellular networks, Starlink offers the lowest QoE for both apps due to its lower throughput.

Our dataset and scripts are available to the research community [1] to facilitate additional replicability studies.

Table 1: Fraction of time spent and fraction of miles driven in each timezone and at each driving speed.

	Distribution of data statistics
Timezone	Pacific: 11% (miles), 15% (time) Mountain: 32% (miles), 29% (time) Central: 25% (miles), 24% (time) Eastern: 32% (miles), 32% (time)
Vehicle speed	0-20 mph: 2% (miles), 17% (time) 20-60 mph: 9% (miles), 13% (time) 60+ mph: 89% (miles), 70% (time)

2 Methodology

We adopt the same methodology as the target paper with a few key modifications. Our measurement campaign was conducted along the same cross-country route on November 1–8, 2024. Table 1 shows the fraction of time spent and the fraction of miles driven in each timezone as well as at each driving speed. Similar to the target paper, we consider three speed bins – low (0-20 mph), mid (20-60 mph), and high (60+ mph) – which act as a proxy to the type of region where the measurements were performed (urban, suburban, and highways, respectively).

Our testbed consisted of four smartphones, each connected to a different network operator (Verizon, AT&T, T-Mobile, Starlink) to *concurrently* measure the performance over all the available networks. Three of the phones were connected to XCAL Solo [5] devices to collect lower-layer cellular KPIs. For Starlink-specific data collection, grpcurl [23] was utilized to fetch and save terminal information from gRPC APIs exposed on the router's local network. Similarly to the target paper, we deployed AWS EC2 cloud servers in California and Ohio, and AWS EC2 Wavelength edge servers in Los Angeles, Las Vegas, Denver, Chicago, and Boston for tests done with Verizon in those cities.

A major difference from the target paper lies in the user equipment (UE). While the original study used Samsung Galaxy S21 Ultra devices with the Snapdragon X65 modem – a state-of-the-art phone in 2021 – we chose Samsung Galaxy S24 Ultra devices with the newer Snapdragon X75 modem to better reflect 2024 conditions. Our aim was to capture the evolution of cellular coverage and performance driven by both infrastructure and end-user device advancements (§5.1). S24 supports CA of up to 4 component carriers (CCs) in 5G-mid/5G-low in the DL direction and in 5G-mmWave in the UL direction, compared to 2 CCs in S21, which, at least in theory, can lead to a significant throughput boost. Recent work [17] reported higher 5G mmWave throughput on the S24 phone compared to the S21 phone, even under lower SINR and MCS, attributing the gains to improvements in the S24's modem and signal processing.

For our LEO satellite measurements, we used a Gen 3 standard Starlink terminal with a dish router with the unlimited "roam" plan. The terminal is tightly mounted on the roof of the vehicle. The UE connects to the Starlink router via an 802.11ax 6e link. The complete testbed setup is shown in Fig. 14 in §B.

A second difference from the target paper lies in the type of measurements we conducted. The target paper executed a suite of tests in a round-robin fashion: a 30-35 DL/UL TCP throughput test using nuttcp, followed by a 20 s RTT test using ICMP ping, and 6 min of application tests per round. This limited the number of collected throughput and RTT samples, as most of the time in each round was spent on application tests. Since backlogged throughput tests and RTT tests are better suited for revealing peak network capabilities, our methodology prioritizes collecting more throughput and RTT samples. Thus, we increased the duration of DL/UL tests to 2 min and the duration of RTT tests to 30 s, and unlike the target paper, we did not measure application performance in real time. Instead, we evaluate two of these representative "5G killer apps" – AR (UL-oriented) and 360^o streaming (DL-oriented) – via trace-based emulation using the throughput and RTT data from the publicly available dataset in the target paper and from our dataset. The emulation methodology is described in detail in §8.

3 Coverage

We begin by comparing the cellular network coverage of the three major US operators between 2022 and 2024. Following the definition used in the target paper, we define coverage for a given cellular technology as the fraction of miles driven under that technology. Fig. 1 presents a bird's-eye view of the cellular network coverage along our driving route, segmented by different technologies, showing a substantial increase in 5G coverage in 2024 compared to 2022 for all three operators. The total 5G coverage has increased from 22%/68%/18% in 2022 (Fig. 2(a) in the target paper) to 49%/94%/45% in 2024 (Fig. 2a) for Verizon/T-Mobile/AT&T, and the high-speed 5G coverage (5G-mid and 5G-mmWave) has increased from 16%/37%/2% to 48%/81%/18%.

Although all three operators demonstrate substantial improvement in terms of 5G coverage in 2024, Fig. 2a shows that Verizon and T-Mobile primarily rely on high-speed 5G technologies. In contrast, AT&T continues to depend significantly on the low-speed, but robust 5G low-band spectrum. Nevertheless, five years after the initial 5G rollout, Verizon and AT&T still rely on LTE along considerable portions (51% & 55%) of the driving route.

We also found that T-Mobile is the only operator with an extensive country-wide 5G SA deployment in 2024 (60.5% vs. only 2.5% in 2022). Verizon only recently started deploying SA services; we found a very small percentage (0.003%) of 5G SA in the 2024 dataset. Finally, for AT&T, we found no 5G SA in any of the two datasets.

We further analyze the coverage based on vehicle speed in Fig. 2b. We observe a notable decline in 5G coverage when moving from low to high vehicle speed bins for Verizon and AT&T, aligned with observations in the target paper. Different from the target paper, T-Mobile still maintains impressive 5G coverage (>90%) on highways in 2024. Additionally, while the coverage of high-speed 5G technologies decreased notably under higher vehicle speeds for all three operators in 2022, our results highlight a shift in deployment strategies in 2024. Specifically, for Verizon and T-Mobile, high-speed 5G coverage remains dominant across all vehicle speed bins, accounting for ≥98% and ≥90% of their total 5G coverage respectively. In contrast, AT&T continues to rely heavily on low-band 5G in regions of mid and, particularly, high vehicle speed (highways).

Similar to the observations in the target paper, only AT&T and Verizon have non-negligible 5G mmWave coverage in 2024. However, there is a notable change for Verizon between the two years. In 2022, both operators' 5G-mmWave was restricted to areas of low vehicle speed, typically downtowns of large cities. In contrast, in 2024, we observe roughly 2.4% 5G-mmWave coverage for Verizon in the 20–60 mph bin. Further analysis revealed that we were able to connect to 5G mmWave from freeways in metropolitan regions such as Los Angeles and Chicago. Interestingly, Verizon's mmWave coverage in the low vehicle speed bin has declined from 35% in 2022 to 24% in 2024, revealing a shift towards increased reliance on 5G-mid band deployments over mmWave.

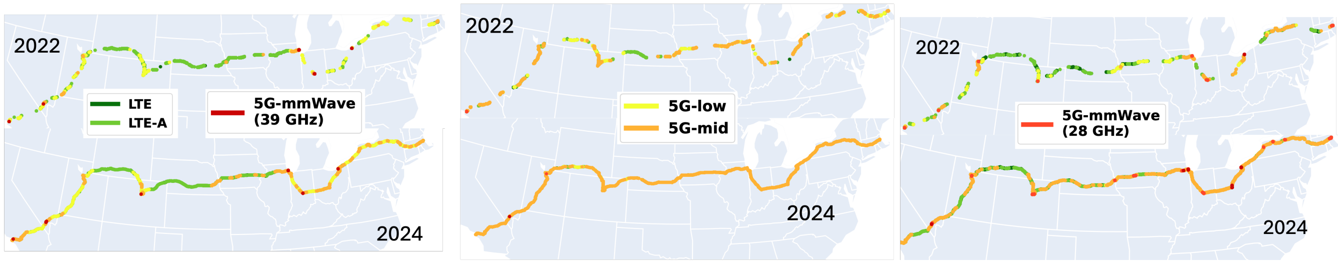
Finally, we break down the coverage by timezone in Fig. 2c. Similarly to 2022, operators continue to adopt diverse deployment strategies in different regions in 2024. For Verizon and AT&T, 5G coverage is noticeably higher in the Pacific and Eastern timezones, likely driven by higher population densities and greater demand in those areas. T-Mobile, in contrast, maintains relatively uniform 5G coverage across all timezones. When focusing on high-speed 5G coverage, we observe again notable regional disparities. For T-Mobile and AT&T, the Pacific timezone has the highest high-speed 5G coverage (28% and 94%, respectively), while for Verizon, the highest high-speed 5G coverage is found in the Eastern timezone (66%). Notably, the Mountain timezone still remains the most underserved region in terms of high-speed 5G coverage in both years for all three operators.

In contrast to 2022, the 2024 deployment landscape shows notable shifts across timezones. Verizon, which had lower overall 5G coverage in the Pacific timezone compared to the Central timezone in 2022, reversed that trend in 2024. For T-Mobile, while the Pacific timezone continues to lead in high-speed 5G coverage, in 2024 we see a significant boost in high-speed 5G across all other timezones.

Summary. 5G coverage has improved significantly in 2024, but two of the three operators (Verizon, AT&T) still provide 5G service on less than 50% of the driving route and they rely (almost) exclusively on the NSA deployment mode. In contrast, the third operator (T-Mobile) provides extensive 5G coverage (94%) along the driving route with a heavy reliance on the SA deployment mode (60.5%). Verizon and T-Mobile have shifted toward broader deployment of high-speed 5G technologies, extending high-speed 5G coverage beyond urban centers, whereas AT&T continues to rely heavily on 5G low-band, particularly on highways. 5G-mmWave deployment remains sparse; Verizon shows some signs of extending it beyond city areas, but, at the same time, it replaces it with 5G-mid in urban areas. The Pacific and Eastern timezones lead in both overall and high-speed 5G availability, reflecting operator prioritization in denser, high-demand regions.

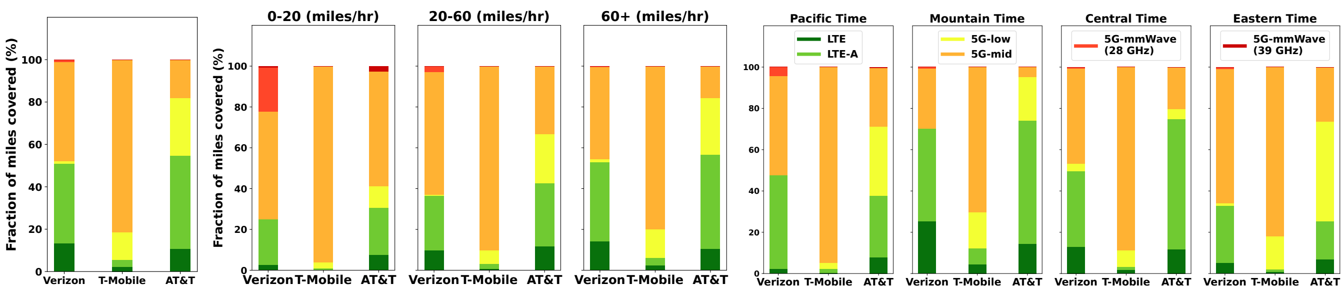
4 Network Performance

Our results in §3 showed a substantial 5G coverage growth for all three operators from 2022 to 2024. To understand whether this



(a) AT&T. (b) T-Mobile. (c) Verizon.

Figure 1: 2022 vs. 2024: Driving route and cellular network coverage.



(a) Overall. (b) By vehicle speed. (c) By timezone.

Figure 2: Cellular technology breakdown per operator in 2024.

Table 2: Cellular performance metrics (25th/50th/75th percentiles) across different technologies: 2022 vs. 2024.

(a) DL throughput (Mbps).

	Verizon				T-Mobile				AT&T			
	LTE	5G-low	5G-mid	5G-mmWave	LTE	5G-low	5G-mid	5G-mmWave	LTE	5G-low	5G-mid	5G-mmWave
2022	2/11/32	3/15/38	31/101/207	401/1035/1508	1/4/21	1/3/23	1/21/234	–	7/22/50	22/50/109	9/46/72	4/740/1334
2024	10/29/71	42/72/128	164/336/566	185/763/1632	1/6/26	34/72/149	143/293/502	–	24/55/101	30/64/118	81/218/409	87/680/1395
2024–2022	8/18/39	39/57/90	133/235/359	-216/-272/124	0/2/5	33/69/126	142/272/268	–	17/33/51	8/14/9	72/172/337	83/-60/61

(b) Uplink throughput (Mbps).

	Verizon				T-Mobile				AT&T			
	LTE	5G-low	5G-mid	5G-mmWave	LTE	5G-low	5G-mid	5G-mmWave	LTE	5G-low	5G-mid	5G-mmWave
2022	3/8/17	5/13/25	7/18/34	38/42/51	2/6/15	1/4/21	1/9/42	–	3/7/12	10/17/29	7/18/33	0/0/0
2024	4/11/22	1/7/51	15/37/65	27/51/109	0/1/4	5/13/34	16/41/72	–	4/10/18	12/27/47	11/29/53	7/48/105
2024–2022	1/3/5	-4/-6/26	8/19/31	-11/9/58	-2/-5/-11	4/9/13	15/32/30	–	1/3/6	2/10/18	4/11/20	7/48/105

(c) Round-trip time (ms).

	Verizon				T-Mobile				AT&T			
	LTE	5G-low	5G-mid	5G-mmWave	LTE	5G-low	5G-mid	5G-mmWave	LTE	5G-low	5G-mid	5G-mmWave
2022	52/64/73	60/69/88	51/57/65	18/24/33	63/70/82	71/84/111	47/62/78	–	61/91/122	56/62/74	36/46/63	88/112/129
2024	54/65/84	58/94/109	41/53/72	16/26/49	77/100/151	68/79/94	58/69/83	–	66/96/129	44/56/75	36/47/59	83/96/121
2024–2022	2/1/11	-2/25/21	-10/-4/7	-2/2/16	14/30/69	-3/-5/-17	11/7/5	–	5/5/7	-12/-6/1	0/1/-4	-5/-16/-8

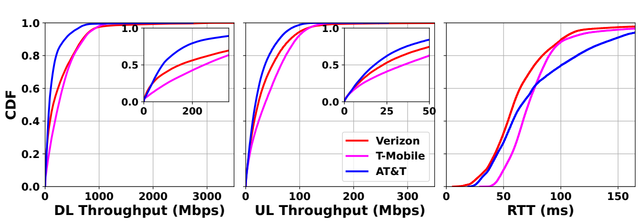


Figure 3: Overall throughput and RTT of all three operators during driving in 2024.

increased coverage translates into better user experience, we now perform a head-to-head comparison of the network performance across the two years.

4.1 Overall Performance While Driving

Fig. 3 presents the throughput and RTT CDFs for the three operators during driving. A comparison against Fig. 3(b) in the target paper reveals that *all three operators exhibit a multi-fold improvement in throughput in 2024 in both traffic directions*. The median DL throughput increased from 16/6/34 Mbps in 2022 to 148/248/77 Mbps in 2024 for Verizon, T-Mobile, and AT&T, respectively. Similarly, the median UL throughput increased from 9/6/8 Mbps to 23/35/18 Mbps. The peak performance also improved, most notably for Verizon – the DL (UL) throughput increased from ~2.2 Gbps (~100 Mbps) in 2022 to over 3.5 Gbps (~350 Mbps) in 2024.

Interestingly, the ranking among operators has changed drastically in 2024 compared to 2022. In the DL direction, AT&T outperformed the other two operators 80% of the time in 2022 (Fig. 3(b) in the target paper), despite its low 5G coverage. In contrast, in 2024, T-Mobile consistently achieves the best performance, followed by Verizon. In fact, the relative gain in median throughput from 2022 to 2024 is the lowest in case of AT&T (2x) in comparison to Verizon and T-Mobile (9x and 41x, respectively). In the UL direction, T-Mobile lagged behind the other two operators 55% of the time in 2022, but it is clearly the best performing operator in 2024, with a median improvement of 5.8x compared to 2.25x for AT&T and 2.5x for Verizon.

On the other hand, *the latency did not follow the throughput trend.* For Verizon and T-Mobile, the 25th and 50th RTT percentiles remain largely the same between 2022 and 2024 (Verizon: 48/60 ms in 2022 vs. 46/59 ms in 2024, T-Mobile: 57/71 ms in 2022 vs. 60/72 ms in 2024). T-Mobile saw a modest improvement from 93 ms to 86 ms at the 75th percentile, but Verizon's 75th percentile increased from 71 ms to 78 ms. AT&T is the only operator that reduced its latency in 2024, with its 25th/50th/75th percentiles having dropped from 57/77/111 ms to 48/66/103 ms. Nonetheless, Verizon still provides the lowest latency in 2024, in part due to the use of edge servers in our experiments with Verizon in large cities, although the gap with T-Mobile reduces drastically, especially above the 80th percentile; and AT&T's latency remains the highest among the three operators about 40% of the time.

Overall, our results show that improving latency remains a complex challenge for operators. While lower layer innovations such as MIMO, increased levels of CA, and the use of wider channels, or improvements in the modem and signal processing capabilities can directly impact throughput, the end-to-end latency is affected by multiple factors including scheduling policies at the base station, prioritization policies (of ICMP vs. TCP traffic) over different technologies (see §4.2), as well as congestion both in the operator's network and the end-to-end path. A recent study [9], based on an Ookla dataset collected in 9 US and European cities, also shows minimal latency improvements from 2020 to 2023, while another study [10] shows that latency increased for two operators in Rome, Italy, between 2021 and 2023. We also used the Ookla Speedtest Connectivity Reports in the first half of 2024 [2] and 2025 [3] (reports for previous years are not available) to calculate the average latency over the 14 states we crossed in our trip; the results show an improvement lower than 2 ms, indicating that the trend of slow latency improvements continues.

4.2 Performance Breakdown By Cellular Technology

Table 2 breaks down the 2022 and 2024 throughput and RTT metrics by cellular technology. We merge the results for LTE and LTE-A, as our focus is primarily on 5G. We make the following observations.
(1) 5G-mmWave still provides the best DL/UL performance at the 50th and 75th percentiles in 2024. In particular, AT&T's mmWave UL performance has improved drastically ([28] reported 0 UL throughput 90% of the time). However, at the 25th percentile, T-Mobile's and Verizon's 5G-mid throughput is higher than AT&T's mmWave throughput in the DL direction; and all three operators' 5G-mid throughput is higher than AT&T's mmWave throughput in the UL direction. Additionally, Verizon's DL 5G mmWave throughput has substantially decreased in 2024 compared to 2022 at the 25th and 50th percentiles (by 54% and 26%, respectively), even though it still remains higher than the throughput of all other technologies. Recall that Verizon extended its 5G mmWave service to freeways outside urban centers in 2024 (Fig. 2b). These newer deployment zones may be less optimized or more prone to mobility-related impairments. Another possible reason for the performance drop is increased congestion in the mmWave bands, as more users are using mmWave-capable devices in 2024 (we elaborate on this in §5.1.1). A similar observation can be made for AT&T's 5G mmWave service in the median case, however, the reduction is much smaller (8%) and the number of samples is also much smaller compared to Verizon (Figs. 2, 2b).
(2) The large improvements in the overall throughput in 2024 (Fig. 3) mostly stem from the boost in the 5G-mid performance with improvements ranging from 3x-14x in the median case. This is true particularly for T-Mobile and Verizon, whose 5G coverage in 2024 is predominantly based on 5G-mid deployments (Fig. 2). In contrast, while AT&T also shows substantial improvements in 5G-mid throughput in 2024, its 5G coverage is still largely dominated by the low-band spectrum, which provides much lower throughput than 5G-mid, as shown in Table 2. This explains AT&T's overall lower throughput in 2024 compared to the other two operators.
(3) The latency shows different trends compared to throughput. For Verizon and T-Mobile, the latency has increased for most technologies in the median case from 2022 to 2024. Specifically, Verizon's median RTT rose by 2% for LTE, 36% for 5G-low, and 8% for 5G-mmWave, while 5G-mid was the only exception, lowering the latency by 7%. T-Mobile shows a similar pattern, with the median RTT increasing by 43% for LTE and 11% for 5G-mid, while 5G-low saw a modest 6% reduction. In contrast, AT&T shows a more favorable trend: the median RTT dropped by 9.6% for 5G-low and by 14% for 5G-mmWave, but slightly increased for LTE and 5G-mid (by 5% and 2%, respectively). These results suggest that operators may apply different policies in prioritizing ICMP traffic in their LTE and 5G networks, further complicating the latency analysis, as discussed in 4.1.
Summary. We observe a drastic improvement in cellular network throughput under driving from 2022 to 2024, driven largely by the maturation of 5G mid-band deployments. T-Mobile and Verizon show the largest throughput boost due to their aggressive mid-band rollouts, while AT&T, with heavier reliance on 5G low-band, sees more modest gains. On the other hand, latency remains a complex challenge, shaped by multiple factors, including backend architecture, scheduling, and traffic prioritization policies, which likely explain the modest or even negative gains observed from 2022 to 2024 for two of the three operators.

4.3 Operator Diversity in Cellular Network Performance

The target paper explored operator diversity in cellular network performance at a given location and time and found that the performance at a given location and time can be highly diverse across operators in both directions. We repeat this analysis for our 2024 dataset in Fig. 4.

While operator diversity still exists in 2024, we observe a fundamental difference compared to 2022. In 2022 (Fig. 6(a) in the target

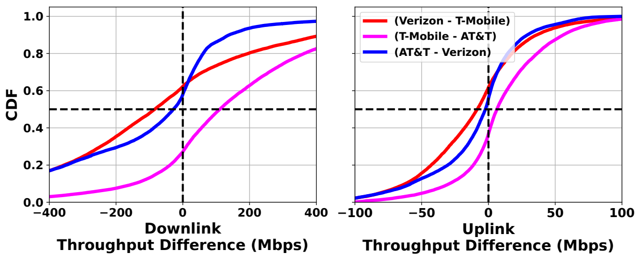
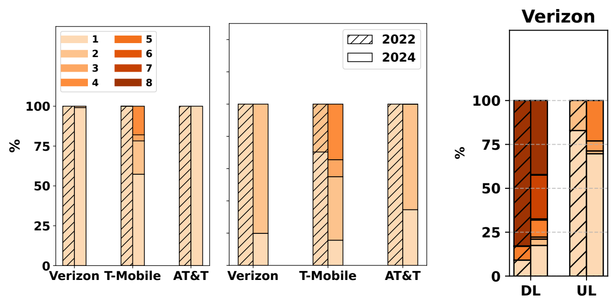
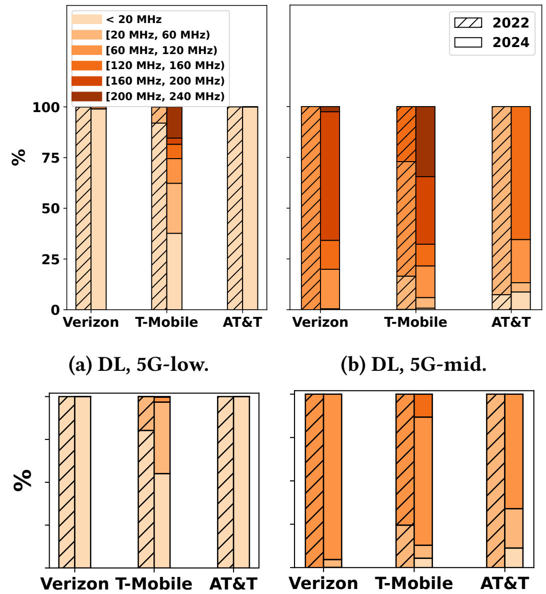


Figure 4: CDF of throughput difference for each pair of operators in 2024.



(a) DL, 5G-low. **(b) DL, 5G-mid.** **(c) 5G-high.**

Figure 5: CA comparison.



(a) DL, 5G-low. **(b) DL, 5G-mid.**

(c) UL, 5G-low. **(d) UL, 5G-mid.**

Figure 6: Sum BW comparison.

paper), the throughput difference CDFs for all operator pairs in both traffic directions were symmetric around 0, indicating roughly equal probability for one operator to outperform the other at a given location and time. In contrast, in 2024, the CDFs are no longer symmetric around 0, especially in the DL direction. T-Mobile, due to its extensive 5G-mid coverage in 2024, outperforms Verizon/AT&T 65%/75% of the time in the DL direction and 60%/65% of the time in the UL direction.

We also observe that the spread of the CDFs widens in 2024 compared to 2022 – especially in the DL direction. The steeper slopes in 2022 reflect smaller, more consistent differences, whereas the flatter CDF curves in 2024 capture the growing divergence in operator capabilities. Nevertheless, the core insight from the target paper still holds – leveraging operator diversity through multi-carrier access continues to offer strong potential for improving overall performance.

5 5G Features

In the previous section, we showed that cellular network performance – particularly for 5G – has improved markedly from 2022 to 2024. To better understand the underlying factors driving this performance boost, this section takes a closer look at two factors that theoretically boost 5G throughput – CA and MIMO – and examines their evolution over the past two years. Although the target paper did not examine these 5G-specific features, we obtained an extended dataset from the authors of the target paper for a deeper exploration of these metrics.

5.1 CA and Aggregate Cell Bandwidth

One of the key innovations 5G introduced to boost performance is the usage of high bandwidth channels (≥ 50 MHz and going up to 100 MHz) and high CA, which aggregates multiple channels (Component carriers – CCs) leading to aggregate bandwidths of up to 800 MHz (in 5G-mmWave). Hence, it is imperative to understand the evolution of CA adoption and bandwidth configurations from 2022 to 2024.

Figs. 5, 6 compare the number of DL/UL aggregated CCs and the corresponding distribution of aggregate cell bandwidth for 5G-low, 5G-mid, and 5G-high (mmWave) in 2022 vs. 2024. Since CA is only performed under heavy traffic, we only use the data collected during download/upload tests for this comparison, and plot the fraction of miles driven under a particular CA/bandwidth configuration over the total miles driven under 5G. We omit the mmWave-related analysis for AT&T and T-Mobile due to the very low 5G mmWave coverage across the driving route for these operators. Note that in 5G-mmWave all CCs belong to the same band and each CC typically provides 100 MHz of bandwidth,[1] i.e., there is a direct mapping between the number of aggregated CCs and the total bandwidth. Hence, we only show the number of CCs for 5G-mmWave. In contrast, in 5G-low and 5G-mid bands, different CCs can belong to different bands[2] and support different bandwidths from 15 MHz to 100 MHz, i.e., a higher CA level does not necessarily lead to higher bandwidth.

5.1.1 Downlink. Overall, we observe a mixed trend for the CA level and the aggregate cell bandwidth across different bands in Figs. 5a-5c and Figs. 6a, 6b.

5G-low. Figs. 5a, 6a show that, for Verizon and AT&T, there's practically no change in the CA level or aggregate bandwidth over the two years. Both operators use a single CC with a bandwidth ranging from 10 to 20 MHz. On the other hand, with T-Mobile, we see more than one CC about 40% of the time in 2024 (vs. no CA in 2022), and 3–4 CCs nearly 20% of the time. This increase in CA is also reflected in the bandwidth distribution; while 2022,

[1]except for occasional 50 MHz primary CCs.

[2]Our classification into 5G-low, 5G-mid in §5.1 is based on the primary CC.

similar to the other two operators, was mainly dominated by 10-20 MHz connections, the aggregate bandwidth exceeds 20 MHz 60% of the time in 2024, with a non-negligible share exceeding 160 MHz. As seen in Table 2, all three operators improved their median 5G-low DL performance in 2024 compared to 2022, but the gain was substantial for T-Mobile compared to the other two operators (nearly 24x vs. 5x for Verizon and 28% for AT&T).

5G-mid. Unlike 5G-low, we observe a clear increase in CA usage from 2022 to 2024 for all 3 operators in 5G-mid (Figs. 5b, 6b). In 2022, Verizon and AT&T relied on single-carrier configurations while T-Mobile used 2 CCs about 30% of the time. In contrast, in 2024, 2-CC aggregation became the dominant setup for Verizon and AT&T, while T-Mobile stands out as the only operator using 3 and 4 CCs.

We note here that these CA patterns are also influenced by the UE model. Recall that the target paper used Samsung S21 devices, which do not support more than 2-CC aggregation. In the case of T-Mobile, it is possible that the operator also allowed for aggregation of 3 and 4 CCs back in 2022, but this is not reflected in the 2022 dataset due to the UE model used by the target paper. On the other hand, both Verizon and AT&T continue to use only 2-CC aggregation in 2024, failing to fully utilize the capabilities of newer UE models.

The higher CA in 2024 leads to a clear increase in the aggregate bandwidth for all three operators compared to 2022. Verizon, which operated exclusively in the 60–120 MHz range in 2022, expands to 120+ MHz over 80% of the time and 160+ MHz over 60% of the time in 2024. T-Mobile exhibits an even more aggressive bandwidth expansion. Most of its connections were within the 60–120 MHz range in 2022, but over 79% of its connections use 120+ MHz bandwidth in 2024, with a significant share (around 35%) reaching 200–240 MHz. In contrast, AT&T, while it also increased its aggregate bandwidth in 2024, is capped out at 120–160 MHz. This aligns with the lower 5G-mid DL throughput observed for AT&T in Table 2 compared to the other two operators, even though it uses the same CA configuration (2-CC) as Verizon. Interestingly, Table 2 shows that Verizon achieves slightly higher 5G-mid DL throughput than T-Mobile at the 50th and 75th percentile,[3] despite the latter's higher bandwidth configurations, suggesting that a few extra 10s of MHz do not necessarily lead to an additional throughput boost.

5G-mmWave. Surprisingly, for 5G-mmWave connections with Verizon, the number of aggregated CCs declined noticeably in 2024 (Fig. 5c). The fraction of 8 CCs dropped by nearly half in 2024 (40% in 2024 vs. 82% in 2022), with 6-CC, 4-CC, and 1-CC configurations becoming more prevalent. This in turn explains the significant 5G-mmWave throughput drop at the 25th and 50th percentile in 2024 compared to 2022 in Table 2. We conjecture that the reduced levels of CA in 2024 are (partly) due to increased congestion in the 5G mmWave bands, as more users have upgraded their devices to advanced models that support 5G mmWave and/or higher CA levels. In contrast, the 75th percentile is higher in 2024, possibly due to improvements in S24's modem and signal processing capabilities. A similar result w.r.t. the performance of the two UE models was recently reported in [17].

5.1.2 Uplink. Figs. 5c, 6c, 6d show that the CA levels and aggregate bandwidth are much lower in the UL direction.

[3]The same holds true even at the 99th percentile.

5G-low, 5G-mid. In 5G-low and 5G-mid, we found that only T-Mobile performed CA, aggregating 2 CCs less than 5% of the time for 5G-low and around 25% of the time for 5G-mid in 2024. In contrast, Verizon and AT&T did not perform UL CA in any of the two years. Hence, we omit the CA breakdown, and only show the aggregate bandwidth breakdown in Figs. 6c, 6d.

Figs. 6c, 6d show limited changes for the UL bandwidth between 2022 and 2024. For Verizon, there is practically no shift in aggregate bandwidth in either band. 5G-low (5G-mid) cells provided 10-20 MHz (60-120 MHz) bandwidth in both years. AT&T also had no change in 5G-low bandwidth (10-20 MHz in both years) but expanded its 5G-mid bandwidth, even without CA. It used exclusively 20-60 MHz cells in 2022, but wider 60–120 MHz cells 60% of the time in 2024. T-Mobile showed the most aggressive expansion of UL bandwidth – using cells with 20-60 MHz aggregate bandwidth (40% of the time) and even 60-120 MHz (<5% of the time) in the low bands in 2024, and introducing cells of 120–160 MHz (about 10%) in the mid bands, the highest among all three operators.

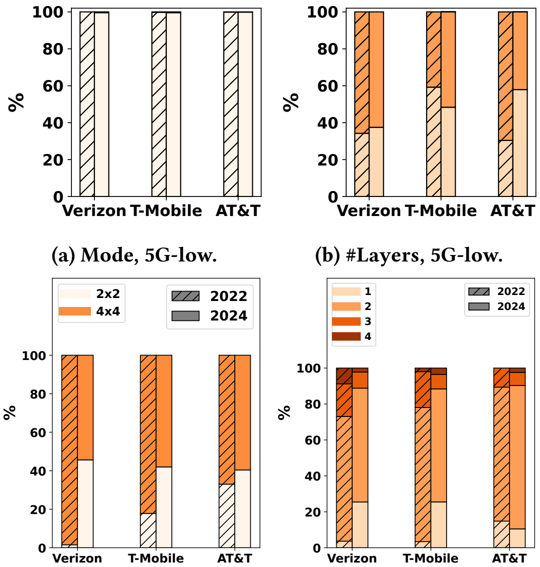
The higher 5G-low aggregate bandwidth in 2024 for T-Mobile led to an increase in its UL throughput compared to 2022 (Table 2). However, AT&T maintained the highest UL performance in 5G-low in both years, in spite of lower bandwidth. In 5G-mid, one can attribute the throughput increase for T-Mobile and AT&T in 2024 vs. 2022 to the higher aggregate bandwidth used in 2024; but a substantial increase in throughput is also observed for Verizon in Table 2. Overall, our results suggest that, for low cell bandwidths, the UE's hardware capabilities and cell's congestion probably play a more important role than the bandwidth itself.

5G-mmWave. In contrast to the DL direction, where the aggregated mmWave bandwidth for Verizon actually decreased in 2024, we observe 3-CC and (primarily) 4-CC CA in the UL direction (400 MHz aggregate bandwidth) for about 25% of the driving distance (Fig. 5c). Recall that the S21 phone used by the target paper supports at most 2-CC CA in the UL direction. That being said, most UL transmissions still use a single mmWave CC in 2024. As a result, Table 2 shows only a small increase in the median 5G mmWave UL throughput (42 Mbps vs. 51 Mbps), but a substantial increase (more than 2x) at the 75th percentile.

5.1.3 Summary. Over the past two years, all three operators expanded aggressively their 5G-mid DL CA levels and aggregate bandwidth. T-Mobile and AT&T also expanded their UL bandwidth, although AT&T does not perform UL CA. In contrast, in the low bands, only T-Mobile introduced CA in 2024 and increased its cell bandwidth. In the mmWave bands, we observed a non-negligible amount of 3- and 4-CC aggregation in the UL direction with Verizon in 2024, which were not supported by the S21 devices used in the target paper in 2022, but, surprisingly, a significant drop in the CA levels in the DL direction. We also found that small bandwidth upgrades (by a few tens of MHz) do not always lead to throughput improvements.

5.2 MIMO

MIMO is another well-established technique for boosting wireless capacity by transmitting mutliple data streams in parallel over multiple antennas. In this section, we analyze how 5G MIMO capabilities have evolved across all three operators. In our analysis, we



(a) Mode, 5G-low.
(b) #Layers, 5G-low.
(c) Mode, 5G-mid.
(d) #Layers, 5G-mid.

Figure 7: MIMO comparison (Downlink).

consider both the MIMO mode of a cell, which reflects the number of Tx/Rx antennas on the gNB, and the number of MIMO layers, which indicates how many of the antennas were actually used to transmit parallel data streams during data download/upload tests.

5.2.1 Downlink. Figs. 7a, 7c compare the distribution of DL MIMO modes in 5G-low and 5G-mid, respectively, in 2022 vs 2024. We observe that all encountered gNBs (across all operators and bands) supported MIMO (2x2 or 4x4) in both years. The same is true for 5G-mmWave (Fig. 15a in §C). However, 5G-low and 5G-mmWave gNBs support exclusively 2x2 MIMO. In contrast, in 5G-mid, 4x4 MIMO was the dominant mode across all three operators in 2022 – 98/82/67% for Verizon/T-Mobile/AT&T – but, surprisingly, its fraction reduced to around 54-59% for all three operators in 2024.

To understand this shift in the MIMO mode trend from 2022 to 2024, we look at the corresponding MIMO layers in Figs. 7b, 7d. Fig. 7d shows that in 5G-mid the combined fraction of 3 and 4 layers is very small (10-25%) for all three operators in 2022 and further reduces (to 10% or less) in 2024. The dominant number of MIMO layers in both years is 2, indicating that, even when higher MIMO capabilities are available, the physical channel often cannot support a high number of layers. Similar trends are observed for 5G-low in Fig. 7b. The fraction of 2 layers across all three operators was only 41-70% in 2022 and further reduced to 42-62% in 2024, in spite the fact that all gNBs supported 2x2 MIMO. Similarly, in 5G-mmWave (Fig. 15b in §C), the fraction of 2 layers reduced from more than 80% in 2022 to about 55% in 2024.

A similar result for 5G-mid, based on a small-scale measurement campaign in Minneapolis and Chicago in 2022, was reported by the authors of [61], who concluded that increasing the MIMO order in future cellular generations might not be the best way to boost throughput. Additionally, equipping gNBs with multiple antennas has negative implications on energy efficiency. Our results suggest that operators have learned a lesson over the past two years and

Table 3: 5G-mmWave uplink MIMO comparison.

	MIMO Mode		MIMO Layers	
	1x1	2x2	1	2
2022	4%	96%	82%	18%
2024	23%	77%	79%	21%

Table 4: HOs per mile along the driving route.

Verizon					
	Total	LTE→LTE	5G→5G	5G→LTE	LTE→5G
2022	1.2	0.74	0.18	0.09	0.19
2024	3.86	1.65	1.5	0.17	0.53
T-Mobile					
	Total	LTE→LTE	5G→5G	5G→LTE	LTE→5G
2022	1.72	0.58	0.4	0.17	0.59
2024	2.69	0.67	1.61	0.08	0.32
AT&T					
	Total	LTE→LTE	5G→5G	5G→LTE	LTE→5G
2022	1.46	0.77	0.24	0.15	0.3
2024	2.86	1.51	0.62	0.16	0.58

either reverted to 2x2 MIMO configurations (by disabling some antennas) or deployed more 2x2 gNBs in 2024.

5.2.2 Uplink. In the UL direction, no operator supported MIMO in 5G-low and 5G-mid. Hence, we limit our discussion to 5G mmWave with Verizon in Table 3, which shows a similar trend as for the DL direction. Although the fraction of 2x2 MIMO is high in both years (96%/77% in 2022/2024), the fraction of 2 layers is very low (only 18%/21% in 2022/2024), again indicating that the channel cannot support MIMO in most cases. Additionally, the fraction of 2x2 MIMO reduced substantially in 2024 compared to 2022 (from 96% to 77%).

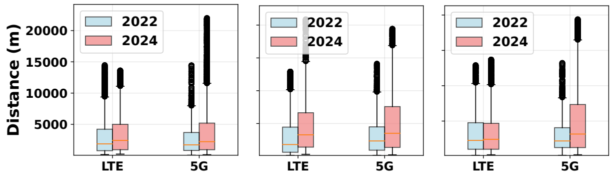
5.2.3 Summary. Our results show that the physical channel often does not enable a high number of MIMO layers (3/4 in 5G-mid, 2 in 5G-low and 5G-mmWave) even when the infrastructure provides support. As a result, all three operators decreased drastically the number of 5G-mid gNBs supporting 4x4 MIMO and Verizon decreased the number of 5G-mmWave gNBs supporting 2x2 UL MIMO in 2024. Overall, increasing the cell bandwidth appears to be a much more promising way to further boost throughput in future cellular generations compared to increasing the MIMO order.

6 Handovers

Handovers (HOs) are essential mobility procedures in cellular networks that ensure seamless connectivity as users move. In this section, we examine how HO behavior, specifically in terms of frequency and duration, has evolved from 2022 to 2024 across different technologies and operators. While the target paper limited its analysis to HOs during throughput tests, we expand the scope to the entire 2022 and 2024 datasets to gain a more comprehensive understanding of this evolution. Note that both datasets include only *active-state* HOs, i.e., HOs occurring while the UE is sending/receiving traffic with the base station (BS).

HO frequency. Table 4 shows the number of HOs per mile for all three operators for 2022 and 2024. The results include the total numbers as well as a breakdown by HO type.

We observe a significant increase in the total number of HOs per mile across all three operators, from 1.2/1.72/1.46 HOs per mile



(a) Verizon. (b) T-Mobile. (c) AT&T.

Figure 8: UE-BS distance during handovers for LTE and 5G.

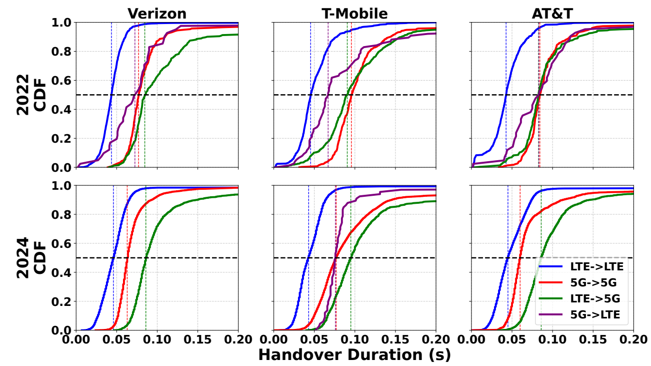


Figure 9: HO duration.

in 2022 to 3.86/2.69/2.86 in 2024, for Verizon/T-Mobile/AT&T. One reason for this is the increased 5G coverage for all three operators and the smaller size of 5G-mid and 5G mmWave cells, which leads to more frequent HOs. In fact, the number of 5G⟶5G HOs shows the largest increase for all three operators, by a factor of 2.6x (for AT&T) up to 8.3x (for Verizon).

Fig. 8 shows a second reason. In this figure, we show boxplots of the distance between the UE and the new BS right after a HO, separately for LTE and 5G BSs, in 2022 and 2024. We calculate the UE-BS distance using the Timing Advance (TA) field.[4] Fig. 8 shows that the distance of the UE to 5G BSs has increased substantially in 2024 for all three operators (particularly for T-Mobile and AT&T) despite the increased 5G coverage. This seemingly counter-intuitive result suggests that all three operators have tuned their HO configurations in 2024 (e.g., the A3 offset of B1 threshold[5]) to enable more aggressive 5G HOs (while the UE is farther away from the gNB) compared to 2022, and contributes to the increase in the number of 5G⟶5G HOs and LTE⟶5G HOs (for Verizon and AT&T). A similar observation was made in [10] for the years of 2021 and 2023 in Italy. In contrast, when we compare the distances to LTE BSs in the two years, we see a smaller increase for Verizon and T-Mobile (relatively to the increase in the distance to 5G BSs) and a slight decrease for AT&T.

Interestingly, for Verizon and AT&T, Table 4 shows a noticeable disparity in the number of 5G⟶5G HOs per mile in 2024 despite both operators having a similar overall 5G coverage of around 50% (Fig. 2). This difference is a result of contrasting deployment strategies. Verizon's 5G is primarily based on mid-band deployments, whereas AT&T relies heavily on low-band 5G (Fig. 2). Since low-band 5G operates at much lower frequencies (≤ 1 GHz) than mid-band (≥ 2.5 GHz), it offers significantly larger coverage per base station, resulting in fewer HOs.

The number of LTE⟶LTE HOs per mile have also increased for all three operators between 2022 and 2024, despite the reduced LTE coverage compared to 2022. While the rise is modest for T-Mobile, the numbers are almost double for Verizon and AT&T in 2024 compared to 2022. Recall that these two operators primarily deploy 5G in NSA mode, where LTE serves as the control plane. As a result, even a 5G⟶5G HO often requires an additional HO of the anchor LTE cell, inflating the LTE⟶LTE HO count in 2024. This inflation is much smaller for T-Mobile, where NSA accounts only for 40% of the operator's 5G deployment in 2024.

Table 4 reveals distinct trends for Inter-RAT HOs, 5G⟶LTE and LTE⟶5G. For 5G⟶LTE HOs, T-Mobile sees a decline in the number of HOs per mile from 0.17 to 0.08 between 2022 and 2024, a direct consequence of its 5G coverage expanding from 68% to 94%, resulting in fewer fallbacks to LTE. In contrast, Verizon and AT&T experience an increase in 5G⟶LTE HOs per mile, despite improved 5G coverage in 2024. This is because their 5G footprint, although larger than in 2022, still covers only around 50% of the route, increasing the likelihood of dropping back to LTE as users move in and out of 5G zones. The increase is much smaller for AT&T, due to the operator's heavy reliance on 5G-low.

Interestingly, the number of LTE⟶5G HOs is consistently higher than the number of 5G⟶LTE HOs for all three operators in both years. This asymmetry stems from the device behavior under idle conditions – to conserve energy, devices often stay on LTE in the absence of active traffic. When a throughput test begins, the device upgrades to 5G, triggering an LTE⟶5G HO. However, once in 5G, the network may not immediately fall back to LTE, particularly during the same test session – resulting in fewer 5G⟶LTE transitions relative to LTE⟶5G. Similar to 5G⟶LTE HOs, T-Mobile sees a decline in the number of LTE⟶5G HOs in 2024, due to its extremely low LTE coverage, while the other two operators see an increase due to their balanced LTE/5G coverage.

HO duration. We define the HO duration as the time from the moment the network sends the RRC Reconfiguration message initiating a HO till the moment the random access procedure (PRACH) is completed. Fig. 9 compares the HO duration for different HO types across the two years.

For intra-RAT LTE⟶LTE HOs, the median HO duration remains similar in both years for all three operators. In contrast, for the intra-RAT 5G⟶5G, we notice a substantial drop in the median HO duration – from 77/96/84 ms in 2022 to 63/77/60 ms in 2024 for Verizon/T-Mobile/AT&T. As operators rolled out more 5G gNBs, the likelihood of encountering neighbor cells with better signal strength increased from 2022 to 2024, leading to fewer failures during random channel access, which reduces the overall 5G⟶5G HO duration.

In the case of inter-RAT HOs, for LTE⟶5G HOs, the median HO duration remains unchanged across the two years for all three operators. On the other hand, for 5G⟶LTE HOs, we see a different picture. In 2022, 5G⟶LTE HOs either were triggered by A2 events in §D or occurred due to 5G failures. In contrast, in 2024, we found that the only event-triggered 5G⟶LTE HOs were those in T-Mobile's 5G SA deployments (triggered by B2 events); all other 5G⟶LTE HOs occurred due to 5G failures. Since we do not compute HO duration

[4] TA is used to synchronize the transmission timing of a UE with the BS to compensate for the propagation delay of the radio signals.
[5] A brief description of the HO triggering events is given in Table 5.

in failure scenarios, the 2024 5G→LTE durations are unavailable for Verizon and AT&T. For T-Mobile, we observe a more nuanced trend: although the 2022 HO durations are lower than 2024 up to the 60th percentile, the tail behavior is noticeably worse. The 2022 durations cross the 100 ms mark at the 70th percentile, whereas in 2024, approximately 85% of the HOs complete within 100 ms, indicating tighter control and reduced long-tail delays.

Summary. The total number of HOs per mile increased substantially in 2024 compared to 2022 due to (i) the increased 5G coverage and the smaller size of 5G-mid and 5G mmWave cells, which leads to more frequent 5G→5G HOs, (ii) the use of more aggressive HO configurations, particularly for 5G, which trigger HOs more aggressively, and (iii) the extensive use of 5G NSA by two operators, which often triggers an additional LTE→LTE HO along with a 5G→5G HO. On the other hand, with the exception of 5G→LTE HOs in T-Mobile's 5G SA deployments, the HO duration either remained the same (for LTE→LTE HOs and LTE→5G HOs) or reduced (for 5G→5G) in 2024, likely due to improved 5G cell density, which reduces the probability for RACH failures.

7 Cellular vs. LEO Satellite Networks

Up to this point, our analysis has focused on comparing the coverage, performance, and key 5G metrics of cellular networks between 2022 and 2024. With LEO satellite networks gaining momentum and expected to play a pivotal role in the next-generation of wireless networks, it is imperative to understand how they compare to existing terrestrial deployments. In this section, we present a head-to-head comparison between cellular networks and Starlink's LEO satellite network using the dataset collected in 2024. Note that the target paper did not consider Starlink in their evaluation.

7.1 Network Availability

Before comparing the performance of cellular networks against that of the Starlink network, it is important to understand the availability of the two networks. We analyze the outage rate of the two networks, defined as the fraction of outage duration relative to the total measurement duration. For cellular networks, outages are recorded as "No Service" events logged by XCAL, while for Starlink, the Starlink grpc API directly reports outage intervals.

The three cellular networks did not exhibit any "No Service" events throughout the entire driving route, resulting in a 0% outage rate. In contrast, Starlink experienced outages for approximately 2.03% of the route. To understand where these outages occur, we further categorize them by area type: urban, suburban, and rural. These labels were manually annotated during data collection. Interestingly, nearly 70% of Starlink outages occurred in urban areas – especially dense downtown regions – while the remaining 30% was split evenly between suburban and rural zones. This pattern is consistent with prior work [32], and reflects the challenges posed by urban obstructions like tall buildings, which limit the line-of-sight required for stable satellite connectivity.

7.2 Network Performance

Fig. 10 compares DL/UL throughput and RTT between Starlink and the three cellular operators. The cellular throughput CDFs include all the throughput samples, regardless of the cellular technology.

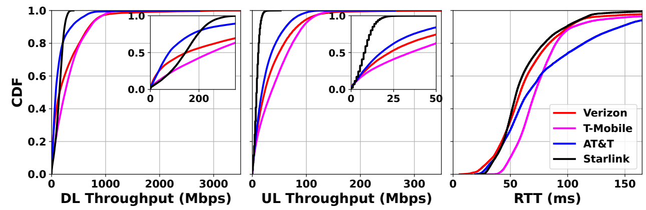


Figure 10: Throughput and RTT comparison of Starlink and cellular networks.

Downlink performance. Fig. 10 (left) shows that Starlink outperforms AT&T (the operator with the lowest DL throughput) about 80% of the time. Its throughput at the 25th/50th/75th percentile is 34/144/196 Mbps vs. 12/77/170 Mbps for AT&T. However, AT&T outperforms Starlink 20% of the time, with a peak throughput of 2.7 Gbps compared to only 406 Mbps for Starlink. Starlink outperforms Verizon around 50% of the time with both operators achieving similar median throughput. However, for the upper 50th percentile, Verizon achieves much better performance, for example 428 Mbps vs. 196 Mbps at the 75th percentile. Finally, Starlink performs similarly as T-Mobile at the 25th percentile, but beyond that, T-Mobile outperforms Starlink by a margin even higher than that of Verizon.

Uplink performance. We notice a completely opposite behavior in terms of UL performance in Fig. 10 (middle); Starlink achieves the worst performance among the four networks, with a median value of only 8 Mbps and a peak value of 52 Mbps vs. 18-35 Mbps and 216-531 Mbps, respectively, for the cellular networks. This result shows that the asymmetry in terms of DL and UL performance is even more pronounced in Starlink compared to cellular networks, highlighting an area for improvement for Starlink.

Similar to previous studies [32], we also found that Starlink's throughput takes its highest values in both directions in rural areas and its lowest values in urban areas, due to obstructions, while cellular network throughput takes its highest values in urban areas due to high availability of high-speed 5G (see Table 6 in §E).

RTT. Interestingly, Starlink overall achieves the best RTT among the 4 networks (Fig. 10(right)). Its 25th/50th/75th percentiles are 46/55/73 ms vs. 46-60/59-72/78-103 ms for the three cellular operators. This result is similar to the result in [27], based on an 860 km driving measurement campaign on the East Coast carried out in the same year as our study, but very different from the result in [32], based on another driving campaign spanning 5 states in 2023, where Starlink's RTT was higher (by 8-10 ms in the median case) than Verizon's and T-Mobile's RTT. Note that the Starlink RTT values reported in [32] are slightly higher than the values in our dataset, while the cellular RTTs for Verizon and T-Mobile are lower than the RTTs in our dataset, confirming again the stagnation (and even deterioration) of cellular network latency we observed in our dataset (Fig. 3, Table 2).

Summary. Starlink provides almost (but not) 100% availability and better RTT compared to cellular networks. Its DL performance is commensurate to that of cellular networks in the median case (100+ Mbps) and significantly better compared to 2/3 cellular networks at the 25th percentile, making it a solid competitor for mobile Internet access in rural areas, where two cellular operators have limited high-speed 5G coverage. However, its peak throughput is bounded at 406 Mbps while 5G-mid and 5G mmWave exceed 1 Gbps, and its UL throughput is much lower than that of cellular networks.

8 Application Performance

The target paper analyzed the performance of four representative latency-critical and bandwidth-intensive "5G killer apps" – cloud-assisted AR, CAVs, 360^o video streaming, and mobile cloud gaming – and showed that cellular networks were not able to support those apps. In this section, we repeat the same analysis for two of these apps, AR (UL-oriented) and 360^o video streaming (DL-oriented), using the source code from the authors of the target paper. Instead of using real-world experiments, we opted for trace-driven emulation, using throughput traces from the 2022 publicly available dataset and our dataset, to enable reproducibility.

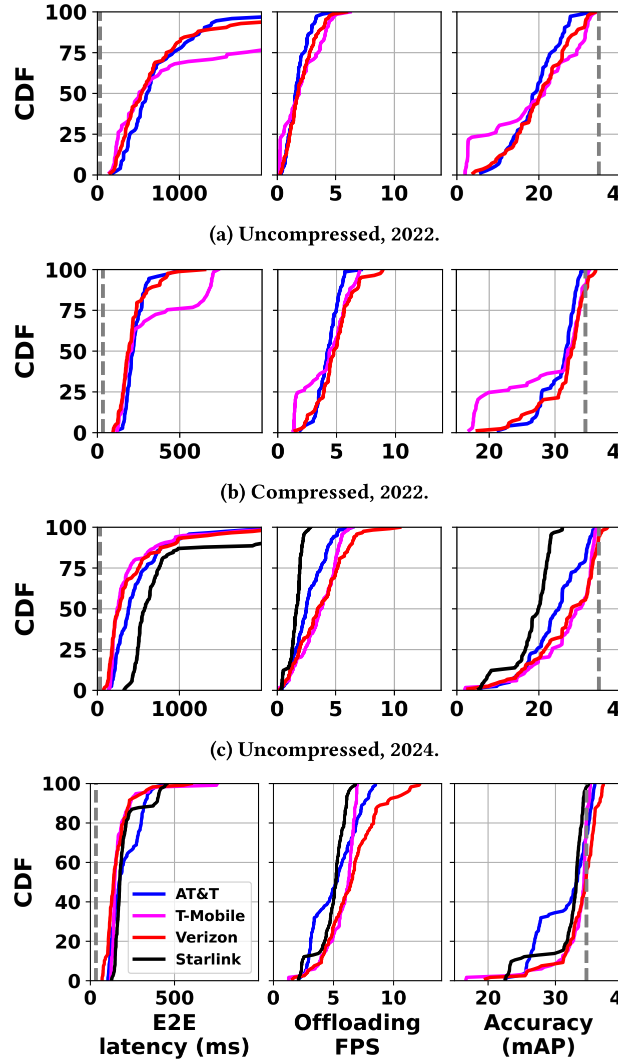
Emulation methodology. We connect the UE to a server over 802.11ax, and emulate the UL (for AR) and DL (for video streaming) bandwidth and latency using Linux tc. Since throughput and RTT traces were collected separately, we merge them as follows. We use fixed-length throughput traces of 40 s with samples recorded every 500 ms. To assign RTTs to the throughput traces, we extract the minimum RTT observed from ping tests for each operator-technology-timezone combination, and assign it to the throughput trace based on the cellular technology of each throughput sample. For Verizon, we further distinguish between traces collected via cloud servers and those using edge servers, assigning separate RTTs accordingly. This minimum RTT represents the propagation delay between the UE and the server; every other delay component (e.g., RAN delay, queuing delay, etc.) is reflected in the throughput trace.

8.1 Cloud-Assisted AR

Since cloud-assisted AR apps that offload powerful computation to an edge server are not yet available on the market, the authors of the target paper built a canonical cloud-assisted AR benchmark Android app that offloads pre-recorded camera frames (at a frame rate of 30 FPS) to a cloud/edge GPU server (with Nvidia A100) that performs object detection in a best-effort manner. We used the same camera dataset [12] and the same methodology to compute the object detection accuracy (mAP metric [16]) as the target paper.

Figs. 11a-11d plot CDFs of the average E2E offloading latency, the number of offloaded frames per second, and the mAP with raw and compressed (H264) frames, for each operator in 2022 and 2024 (the 2024 results also include Starlink). With a frame rate of 30 FPS, the target E2E latency is 33 ms. The offline accuracy is 38.45%. Similar to [30], we consider the offloading performance to be satisfactory if the mAP score of the application with offloading is within 90% of the offline accuracy (34.6%). We make the following observations.

(1) In spite of the different methodology, the results for 2022 (Figs. 11a, 11b) are very similar to those in the target paper (Figs. 18a, 19a) – similar median values, similar relative performance among the three operators, and even similar shape for some CDFs – and the main conclusion from the target paper still holds: *cellular networks were not able to support cloud-assisted AR under driving in 2022.* Even with compression, the median E2E latency in 2022 is 191-217 ms – 5.8x-6.6x that of the target value. As a result, the app achieves a median offloading frame rate of only 4.3-4.8 FPS and mAP of 31.6-32.5% (82-85% of the offline mAP). The performance is much worse without compression, with a median E2E latency of 510-610 ms, median offloading frame rate of only 1.6-1.9 FPS, and median mAP of 19.2-21.3% (50-55% of the offline accuracy).



(a) Uncompressed, 2022.

(b) Compressed, 2022.

(c) Uncompressed, 2024.

(d) Compressed, 2024.

Figure 11: 2022 vs. 2024: AR performance.

(2) The performance improves drastically in 2024, mainly due to the higher bandwidth provided by all three cellular operators. The median E2E latency, offloading frame rate, and mAP with raw/compressed frames is 243-380 ms/137-171 ms, 2.5-3.8 FPS/5.3-6.5 FPS, and 24.8-30.1%/33.3-34.5% (64-78%/87-90% of the offline accuracy), respectively. The app achieves satisfactory accuracy about 46% of the time with Verizon, 27% with AT&T, and 19% with T-Mobile.

(3) Figs. 13a, 13b, which plot the accuracy vs. the percentage of high-speed 5G for each run with a cloud/edge server, confirm two more findings from the target paper: *high-speed 5G improves the worst-case performance compared to 4G/5G-low*, and *the use of an edge server boosts the performance regardless of the cellular technology.* Note that in 2024, all the runs with an edge server experience almost 100% high-speed 5G coverage, as the operator significantly expanded its 5G mmWave/midband coverage in large urban centers (where the AWS Wavelength servers are located).

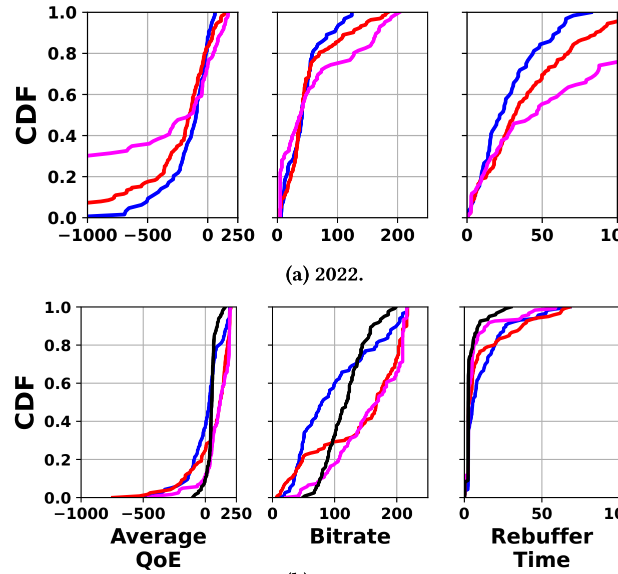
(4) In spite of its lower latency compared to cellular operators (Fig. 10 (right)), Starlink provides the worst AR performance due to its much lower UL throughput (Fig. 10 (middle)). The gap is particularly pronounced with raw frames, where the median E2E latency, offloading frame rate, and mAP with Starlink are 576 ms, 1.7 FPS, and 19.9% vs. 380 ms, 2.5 FPS, and 24.8% with the worst-performing operator. The gap closes substantially with compressed frames that reduce the bandwidth requirements significantly (174 ms vs. 171 ms, 5.2 FPS vs. 5.3 FPS, 33.1% vs. 33.3% mAP). However, Starlink provides satisfactory accuracy only 2.4% of the time.

(5) Our results show that *application-level optimizations developed in the pre-5G era, such as frame compression and local tracking [6, 14], remain relevant even in 2024, in spite of the drastic improvements in cellular performance over the past two years.* Compression, which was shown to significantly improve performance in the target paper, helps the app achieve satisfactory accuracy 25-50% of the time with the 2024 traces. This result is achieved in spite of the app offloading at most 12.5 FPS (Fig. 11d (middle)), thanks to local tracking, which helps mask the long E2E latency.

8.2 360^o video streaming

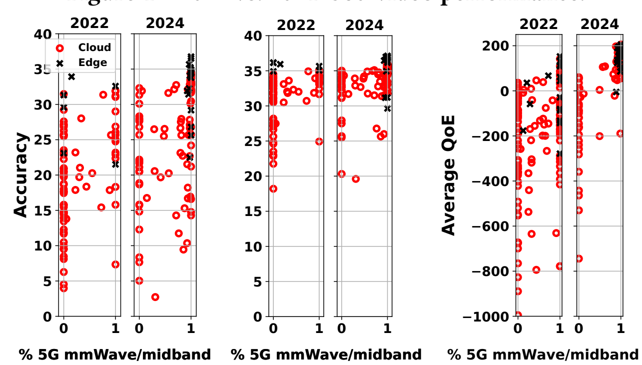
We used the 360^o video streaming system from the target paper and the same YouTube videos for our evaluation. The system uses Puffer, an open source video streaming server [64], with BBA [33] as the ABR algorithm, and a custom mobile client. We encoded each video into 5 different quality settings (5, 10, 50, 100, 250 Mbps), adding one extra setting (250 Mbps) compared to the target paper, since the cellular network bandwidth increased drastically in 2024. Each playback session runs for 40 s. We used the same video chunk QoE metric [68] as the target paper with $\lambda = 1$ and $\mu = 250$, following the guideline in [68], which results in a theoretical maximum QoE value of 250 (assuming no rebuffering and no bitrate change). All other settings are the same as in the target paper. Fig. 12 plots CDFs of the average QoE, average bitrate, and rebuffering time per session for all operators in 2022 and 2024. We make the following observations.

(1) Although the results for 2022 are quantitatively different from the target paper, due to the inclusion of one extra bitrate, they still confirm the main conclusion of the target paper, similar to the AR results: *cellular networks were not able to support 360^o video streaming under driving in 2022.* The QoE is negative 75-90% of the time with all three operators, with a median value between -152 and -96 and a maximum value of only 62-170. Although the average bitrate exceeds 150 Mbps for a few sessions with T-Mobile and Verizon, the median bitrate is only about 40 Mbps for all 3 operators. Similarly, the rebuffering time is very high, with median values of 22-45%. In particular, for T-Mobile, 25% of the sessions experience a rebuffering time of 100%. Note that the QoE and the rebuffering time are much worse in our trace-driven emulation compared to the results reported in the target paper, even though the median bitrate is similar, due to the additional encoded bitrate of 250 Mbps we used in our evaluation. Although this bitrate can occasionally be supported, the highly fluctuating network conditions under driving often result in an increased rebuffering time when the ABR



(a) 2022.
(b) 2024.

Figure 12: 2022 vs. 2024: 360-video performance.



(a) AR (raw). (b) AR (H264). (c) 360-video.

Figure 13: Impact of high-speed 5G and edge servers.

algorithm aggressively selects to request a chunk at 250 Mbps. Interestingly, AT&T, has very few runs with an average bitrate above 100 Mbps, and as a result, it exhibits the lowest rebuffering time. This is because AT&T's DL throughput is rarely higher than 250 Mbps (Fig. 3), and hence the player rarely requested chunks at that bitrate.

(2) The performance improves drastically in 2024. The rebuffering time is less than 5% for 48-71% of the time, with a median value of only 2.9-5.6%, and the median bitrate increases to 79-168 Mbps. As a result, the QoE is positive 60-90% of the time, with a median value of 32-121. The improvement is more pronounced for T-Mobile and Verizon, the two operators with the largest 5G-mid coverage in 2024.

(3) Fig. 13c shows that the combination of high-speed 5G and an edge server improves the worst-case QoE in 2022 but almost always results in very good to excellent QoE in 2024. However, the use of edge servers is less critical compared to the AR use case, especially in 2024, as video streaming can tolerate latencies due to buffering. In fact, T-Mobile achieves slightly better performance than Verizon in 2024 (Fig. 12b) due to its extensive fast 5G-mid coverage in spite of the absence of edge servers. We conclude that *5G-mid performance* *in 2024 is sufficient to provide high QoE for 360^o video streaming under driving*, but coverage holes and fallbacks to 5G-low/LTE still hurt the performance.

(4) Starlink provides the lowest rebuffering time among the four operators but also lower bitrates than two cellular operators (Verizon and T-Mobile), as the ABR algorithm requests chunks at high bitrates (100 Mbps and 250 Mbps) less often over Starlink compared to T-Mobile or Verizon. As a result, Starlink provides the highest worst-case, but the lowest best-case QoE. This result is a direct reflection of Starlink's lower DL throughput relative to the DL throughput of the cellular operators (Fig. 10 (left)).

9 Related Work

5G measurement studies. Since its initial roll-out in 2019, numerous studies have evaluated various aspects of 5G networks including performance [7, 10, 11, 20, 28, 29, 37, 41, 42, 51, 52, 55, 58, 60, 63, 66], latency [19], handovers [22, 31, 35], carrier aggregation [67], resource allocation [15], power consumption [55], impact on application QoE [10, 38, 55], beamforming [17, 54], roaming [10, 21], multi-carrier access [13], and throughput prediction [8, 53, 67]. Most are limited in geographic scope, focusing on one [11, 22, 41, 42, 51, 53–55, 63, 66] or a few cities [10, 15, 17, 18, 21, 29, 52, 60, 61, 66], and they do not cover rural or suburban areas. Additionally, most of these studies generally cover short time spans, from a few days to weeks [15, 29, 52–55, 60, 61, 63] or a few months [20–22, 41, 42]. A few studies use large datasets collected via driving measurement campaigns similar to ours [7, 13, 31] or over extended time spans [13, 15, 17, 67] but each of them focuses on a specific 5G aspect – handovers [31], multi-carrier access [13], root causes of poor performance [7], CA [67], resource allocation [15], or beamforming [17], and none of them tracks performance evolution over time, unlike our work. Finally, some works study the evolution of 5G over extended time periods using crowdsourced datasets from commercial or custom bandwidth measurement apps [9, 37, 65] or collected on the operator side [58]. Although these datasets offer broader geographic and user coverage compared to cross-country drives, they do not capture information such as user mobility or lower layer features, they do not obtain measurements over different networks at the same location and time, and they do not analyze the performance of specific applications.

The work closest to ours is [10] (and its shorter version[11]), in which the authors study the evolution of 5G NSA in Rome, Italy, via two large-scale measurement campaigns in December 2020-January 2021 and in March-November 2023. Their data collection campaigns span extended time periods (2 and 8 months vs. 8 days in our work and in [28]) but have limited geographic coverage (a handful of indoor and outdoor locations in one city vs. a cross-country drive in our work and [28]). Similar to our work, the results in [10] show higher 5G coverage, more aggressive use of CA, and more aggressive 5G HOs in 2023 compared to 2021. In contrast to our results, which show drastic DL/UL 5G throughput improvements in 2024 vs. 2022 for all three operators, the results in [10] show reduced DL throughput for one operator and reduced UL throughput for the other operator. Interestingly, the authors in [10] report higher RTT in 2023 compared to 2021 for both operators considered in that study, reinforcing our conclusion that latency remains a major challenge for 5G networks.

In summary, our work takes a unique approach by replicating the study in [28], driving along the same route from the West to the East Coast, while simultaneously measuring the performance of all three major US operators, and studying both network and application performance. Additionally, we expand the work in [28] by performing measurements with Starlink and exploring the impact of lower layer features (CA, bandwidth configurations, and MIMO) on network performance.

Starlink Measurement Studies. Since the launch of Starlink, several works have measured various aspects of the Starlink network including throughput and delay [24, 26, 27, 32, 45, 46, 49, 50, 56, 57], TCP performance [25], browsing [36] and multimedia performance [70], gateway placement [4], and the impact of cloud on LEO communication [44]. The work in [34] proposed a methodology to democratize global visibility into LEO satellite networks. With the exception of [27, 32], all these works perform measurements from *fixed* locations. Furthermore, only a handful of works [27, 32, 45] have performed a head-to-head comparison between Starlink and cellular networks. Among them, [27, 32] use a measurement methodology similar to ours, conducting measurements during long drives on the East Coast and Midwest, respectively. Our cross-country measurement campaign confirms several of the findings in [27, 32] with respect to outage, performance, and impact of area type. Interestingly, our RTT results (§7.2) agree with those in [27], which were obtained in the same year as our study, but are different from those in [32, 45], which were obtained more than a year earlier, suggesting that Starlink has improved its latency over the past one year, unlike cellular networks.

10 Conclusion

The 2022 study [28] offered the first comprehensive, large-scale characterization of operational 5G networks in driving scenarios, assessing coverage, performance, and mobile application QoE across the US. To assess how 5G has evolved at its midlife, we conducted a replicability study in 2024 along the same coast-to-coast route.

Our results reveal substantial improvements in both coverage and throughput across all three major US operators, largely attributable to aggressive 5G-mid deployments, but modest or no improvement in latency. This progress in 5G-mid deployment has led to a marked enhancement in the QoE for two "5G killer" applications analyzed in the original study. However, coverage holes and fallbacks to 5G-low or LTE still hurt the performance, and application-level optimizations developed in the pre-5G era are still needed, even in areas with excellent 5G-mid or 5G-mmWave coverage.

To broaden our analysis, we compared these terrestrial network improvements with Starlink's LEO satellite network. Our results show that, while non-terrestrial systems now offer competitive median downlink speeds and RTTs, they continue to fall short in peak downlink speeds and overall uplink performance.

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Table 5: LTE/5G-NR HO triggering events.
(M = measurement, C = serving cell, N = neighboring cell, H = hysteresis, Θ = threshold, Δ = offset)

Event Type	Event Description	trigger Condition
A1	Serving cell becomes better than a threshold	$M_S > \Theta_{A_1} + H_{A_1}$
A2	Serving cell becomes worse than a threshold	$M_S < \Theta_{A_2} - H_{A_2}$
A3	Neighboring cell becomes offset better than the serving cell	$M_N > M_S + \Delta_{A_3} + H_{A_3}$
A4	Neighboring cell becomes better than threshold	$M_N > \Theta_{A_4} + H_{A_4}$
A5	Serving cell becomes worse than a threshold and neighboring cell becomes better than another threshold	$M_S < \Theta^S_{A_5} - H_{A_5}$ $M_N > \Theta^N_{A_5} + H_{A_5}$
A6	Neighboring cell becomes offset better than the serving cell	$M_N > M_S + \Delta_{A_6} + H_{A_6}$
B1	Inter-RAT neighbor becomes better than threshold	$M_N > \Theta_{B_1} + H_{B_1}$
B2 (5G only)	Primary cell becomes worse than a threshold and inter-RAT neighbor becomes better than a threshold	$M_S < \Theta^S_{B_2} - H_{B_2}$ $M_N > \Theta^N_{B_2} + H_{B_2}$
P	Periodic reporting of serving and neighboring cell's radio signal quality.	N/A

Table 6: Starlink and cellular performance by area type.

(a) Urban

	Verizon	T-Mobile	AT&T	Starlink
DL Throughput	104/285/632	136/324/602	46/180/404	41/117/175
UL Throughput	18/42/75	35/59/84	15/32/57	2/5/8
RTT	26/35/52	50/59/67	33/41/56	44/57/81

(b) Suburban

	Verizon	T-Mobile	AT&T	Starlink
DL Throughput	25/143/465	77/228/442	33/70/197	79/134/184
UL Throughput	9/24/54	10/34/66	8/18/35	4/7/10
RTT	47/65/81	59/69/86	49/76/125	47/57/75

(c) Rural

	Verizon	T-Mobile	AT&T	Starlink
DL Throughput	37/132/386	99/245/450	34/75/143	95/152/203
UL Throughput	7/20/44	10/31/62	6/16/33	5/8/12
RTT	49/59/78	64/76/88	53/67/99	46/55/72

Appendix

A Ethics

This study was carried out by PhD students and faculty. We purchased multiple unlimited cellular data plans from all three US carriers and our experiments comply with their customer agreements. This work does not raise any ethical concerns.

B Measurement testbed

Fig. 14 shows the testbed used in our experiments.

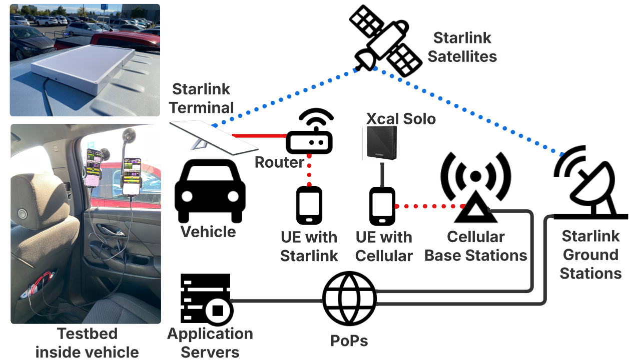
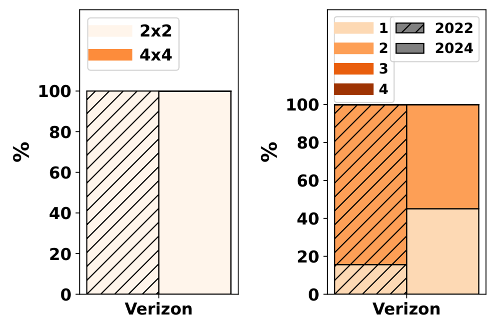


Figure 14: Overview of our measurement testbed.

C 5G-mmWave MIMO

Figs. 15a, 15b compare the MIMO mode and number of MIMO layers, respectively, for 5G-mmWave with Verizon in the DL direction in 2022 vs. 2024.



(a) Mode, 5G-high. **(b) #Layers, 5G-high.**

Figure 15: MIMO comparison, 2022 vs. 2024 (Downlink).

D Handover events and Parameters

Table 5 describes the various LTE/5G-NR HO-related reported events.

E Cellular vs. LEO Satellite Networks

Table 6 shows the performance of Starlink and cellular networks differentiated by area type.