Mapping Cellular Network Evolution and Infrastructure Criticality: A Nationwide Analysis

Varshika Srinivasavaradhan, Owen Park and Elizabeth M. Belding
Dept. of Computer Science; University of California, Santa Barbara
{varshika, ojpark, ebelding}@ucsb.edu

ABSTRACT

The introduction of 5G technology has changed the mobile broadband landscape, yielding faster speeds, lower latencies, and potentially more widespread coverage. In this paper, we study the evolution of US cellular technology, with a focus on 5G, from 2021 to 2023 through the lens of Ookla Speedtest performance and cellular infrastructure deployment. Specifically, we analyze how US cellular network coverage and performance evolved during this period, characterizing improvements at multiple geographic granularities, examining differences between urban and rural performance, and evaluating the availability and performance of "Fast 5G." Then, we investigate the impact of cellular infrastructure, studying the relationship between infrastructure deployment density and network performance and the growth in infrastructure during this time period. Our findings show that, broadly, mobile network performance improved, though the improvement in some states and regions was far greater than in others. For instance, some states show an increase in download speeds of over 200%, while other states show little to no improvement. Cellular deployment density also grew during this period, is approximately 15 to 40 times higher in urban areas than in rural areas, and is strongly correlated with population density. We find that higher cellular deployment density is generally associated with improved network performance; however, the growth in deployment density does not always align with performance gains, as evidenced by weak correlations between increases in density and improvements in performance metrics. We conclude with recommendations about the need for more granular data about cellular technology infrastructure, deployment dates and location data to better inform policymakers about targeted investments in additional cellular infrastructure.

1 INTRODUCTION

Mobile broadband has become indispensable; 94% of Internet users worldwide accessed the Internet via their smartphone in 2023 [24]. More than 60% of Web traffic worldwide occurred via mobile broadband in 2023 [20]. 15% of Americans do not have fixed broadband access at home, and rely instead on mobile phones as their means of Internet access [13]. In most developing countries, mobile broadband (3G or above) is the primary way, and often the only way, to connect to the Internet [14]. This widespread usage and dependence on mobile broadband networks to access healthcare, financial, and educational services necessitates understanding both the availability and quality of mobile broadband access.

Since its inception in 2019, there has been an explosion of 5G network deployment across the United States (US) and worldwide [8, 9, 15]. In the US, 5G deployment has rapidly evolved, driven by the Federal Communications Commission's (FCC) strategic spectrum allocation across high, mid, and low-frequency bands [6]. The goal of this approach has been to enhance the coverage and capacity of 5G networks, addressing the increasing demand for higher data rates and improved connectivity. A significant initiative in this context is the 5G Fund for Rural America, established in 2020, which represents a financial commitment of up to $9 billion. This initiative seeks to extend 5G services to under-served rural areas, particularly targeting regions that have historically lacked adequate 4G LTE or 3G service. The goal is to bridge connectivity gaps and promoting equitable access to advanced mobile broadband.

It is within this context that we study the evolution of 5G in the US from 2021 to 2023. Specifically, we analyze how US cellular network coverage and performance have evolved during this period, characterizing improvements by state and US region, and examining differences between urban and rural performance. To do so, we utilize Ookla® Speedtest® performance data [10] as well as mobile broadband coverage data from the FCC and the National Broadband Map [16]. Ookla Speedtest is a tool that allows users to evaluate the instantaneous performance of their Internet connection. While the performance measured by an individual speed test can be influenced by many factors, including but not limited to signal strength, device type, and network load, aggregating and analyzing a large volume of these tests over time helps identify patterns and trends in network performance. Specifically, we utilize Ookla public data, an aggregated version of crowdsourced Speedtest data that is released quarterly.

The National Broadband Map provides information about the internet services available to individual locations across the country, including maps of mobile coverage, as reported by Internet Service Providers (ISPs). For mobile broadband, the map provides detailed data, differentiating coverage by cellular technology, such as 3G, 4G LTE, and 5G. Specifically for 5G, there are two speed thresholds that depend on the 5G technology and frequency spectrum utilized. One represents the standard 5G with a minimum speed threshold of 7 Mbps download and 1 Mbps upload. The other signifies a higher minimum speed threshold of 35 Mbps download and 3 Mbps upload. This is also the highest speed that the FCC denotes for mobile broadband [21].

Our study focuses on utilizing these datasets to track the growth and evolution of US cellular networks from 2021 to 2023. This approach allows us to identify trends and patterns in performance and infrastructure deployment and highlight regions that might require investment in additional infrastructure. By examining changes in network performance at multiple spatial granularities, our goal is to provide a detailed picture of mobile broadband access and its development. Specifically, we focus on two key questions: *(1) How has US cellular network coverage and performance evolved over time?* and *(2) What is the relationship between cellular infrastructure density and measured Speedtest performance?*

To answer these questions, we integrate Ookla Speedtest data with both publicly available and proprietary information on 4G and 5G cell tower locations, as well as demographic data from the US Census Bureau. Our research draws upon telecommunications and policy analysis to quantify the current state of mobile access in the US and provides insights to inform policymakers on decisions regarding infrastructure investments and network optimization. In summary, our analysis of US cellular network performance from 2021 to 2023 yields the following key findings:

- The 75^{th} percentile download speed increased from approximately 100Mbps to 300Mbps, median upload speeds rose by 75%, and latency decreased by 30%.
- Significant performance disparities between urban and rural areas exist, with urban median download speeds reaching 200 Mbps compared to 75 Mbps in rural areas.
- Higher cellular infrastructure density is associated with better network performance, including a 56% increase in median download speeds, a 66% increase in median upload speeds, and a 20% reduction in latency. The cellular deployment density in urban areas is 15 to 40 times higher than in rural areas.
- The correlations between increases in deployment density and performance improvements are weak, suggesting that other factors also play significant roles in influencing performance outcomes.
- 86% of US census blocks intersect with “Fast 5G”[1] areas, with most of this coverage from urban areas: 96% of US urban land area has Fast 5G coverage compared to 30% of rural land area. Areas identified as Fast 5G have speeds significantly above the 35/3 Mbps threshold, with median download speeds reaching 200 Mbps and median upload speeds of 25 Mbps, which are approximately twice as high as those in non-Fast 5G areas.

2 DATASETS

In this section, we describe each of the datasets we utilize in our study and our strategy for integration and analysis.

2.1 Ookla Public Data

The Ookla Open Data Initiative [7] has made an aggregated version of its global crowdsourced Speedtest data available to the public quarterly (e.g. every three months) since January 2019 [5]. To create this dataset, Ookla aggregates individual measurement data into zoom level 16 web mercator tiles (approximately 610.8 meters by 610.8 meters at the equator), each identified by a unique quadkey. The dataset is filtered to only contain measurements taken with GPS location to ensure accurate mapping of speed measurements. Measurements are then averaged, separately for fixed and mobile broadband, every quarter for each tile. The result is made publicly available. The public data for each tile includes averaged download speeds, upload speeds, ping latency, latency under load, the number of measurements during that quarter, and the number of unique devices used to take measurements.

For our study, we utilize mobile network Speedtest data from the first quarter of 2021 to the fourth quarter of 2023.

Speedtest measurements. Ookla® Speedtest® is a tool that allows users to evaluate the instantaneous performance of their Internet connection through either a web-based portal or a mobile application. The test measures download speed, upload speed, and latency at the user’s current connection point. To perform the measurement, Ookla Speedtest uses the user’s location to select a group of geographically close measurement servers, and then picks the server with the lowest latency as the test endpoint. The test dynamically scales by using multiple parallel connections to fully saturate the bottleneck link. To maintain high-quality data, Ookla manages a network of tens of thousands of servers and regularly removes those that underperform. Therefore, each test result provides a snapshot of Internet performance at that specific moment and location and that reflects the current network traffic to the selected server. When aggregated, these individual measurements can provide a comprehensive view of connectivity in a specific geographic area, capturing variations over time, location, and network load. Although Internet access quality can vary significantly within small

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[1] For our analysis, we refer to the H3 hexagons stated by the FCC’s National Broadband Map as having 5G availability with a minimum speed threshold of 35/3Mbps as "Fast 5G".

areas due to factors like subscription plans (prepaid vs postpaid), time of the day, type of connectivity (residential vs. business), and signal strength, the aggregated data nevertheless offers valuable insight into longitudinal and regional performance trends.

Limitations: Previous research has identified potential limitations of crowdsourced network performance metrics [29, 32, 40]. Crowdsourced tests are inherently uncontrolled, and therefore can introduce biases related to the test-taker, geographic location, network conditions (including congestion or poor service or subscription plan differences), and the characteristics of the test-taking equipment [34]. These biases make it challenging to definitively characterize Internet connectivity in a specific tile. Nevertheless, our use of three years of aggregated data, when grouped over space and time, measures a wide range of usage scenarios and trends that can augment understanding of mobile internet availability and quality and also identify areas that lack enough measurements for comprehensive analysis.

2.2 National Broadband Map Data

The FCC measures cellular network availability through data collection efforts that include self-reported data from service providers and supplemented by crowdsourced data from users. This data is then mapped in the National Broadband Map [16], which provides a comprehensive view of connectivity across the nation. This data is organized into coverage maps using H3 hexagonal cells at resolution 9. Each hexagonal cell is associated with specific attributes that detail the availability and quality of mobile broadband service. For each technology type, the data includes polygon geometries in ESRI Shapefile or GeoPackage formats, along with attributes such as minimum download and upload speeds. These speeds vary depending on the technology; for example, minimum download speeds are specified as 0.2 Mbps for 3G, 5.0 Mbps for 4G LTE, 7.0 Mbps for 5G NR and 35.0 Mbps for Fast 5G. Additionally, the dataset indicates whether the speed values are only for outdoor stationary environments or for both outdoor stationary environments and in-vehicle mobile environments. Recently, the FCC made the latest fixed and mobile broadband coverage data for each technology at various geographies, including state, county and congressional district, publicly available [23]. This data supports research to understand the distribution of high-speed internet access, identify under-served areas, and inform decisions regarding broadband infrastructure investment and policy formulation.

Limitations: Accurately pinpointing areas with high-quality access versus those with limited or no access is inherently challenging due to the lack of complete and accurate coverage data. While serving as a general indicator of connectivity nationwide, the National Broadband Map has been criticized for overestimating fixed and mobile internet availability [28, 33, 41]. The enactment of the Broadband DATA Act in 2020 highlights ongoing efforts to address these issues by allowing individuals to challenge carrier maps through real-world speed tests submitted to the FCC. However, the complexities involved in this challenge process underscore the current gaps in mobile broadband mapping science and the need for improved measurement practices to ensure more accurate and reliable data on coverage and performance.

2.3 Cellular Infrastructure Datasets

A cell tower, or base station, is a physical structure that hosts multiple antennas to provide cellular coverage. In contrast, cells are the individual sectors or areas served by these antennas, each with a unique identifier. A single cell tower can support multiple cells, and each cell on the same cell tower can represent different network access types (e.g., UMTS, GSM, CDMA, LTE, 5G NR) and cover distinct geographic areas around the tower. With this in mind, our mobile infrastructure data comes from three sources: (i) OpenCellID, a public crowdsourced dataset of cell location data; (ii) Ookla, another public crowdsourced dataset that provides data about cell tower locations; and (iii) Tower Maps, a proprietary dataset sourced from providers with the locations of cell towers.

OpenCellID: OpenCellID [19] maintains a global, crowdsourced database of individual 4G and 5G cellular network cell locations. Each entry includes geographic coordinates of the cell and an accuracy metric that gives the radius, in meters, within which the cell can reliably be located. The accuracy metric is important since the reported location in OpenCellID can either be exact (collected from the telecom company) or calculated through triangulation and averaging of multiple crowdsourced measurements [1–3]. This dataset is continuously updated, making it a valuable resource for researchers and analysts seeking information about the spatial distribution and density of cellular network infrastructure.

Ookla: Ookla launched the Ookla 5G Map [4] in May 2019 to track the global expansion of 5G networks. The 5G Map currently catalogs over 145,000 deployments by 233 providers across 142 countries. Each entry in Ookla's dataset includes the provider name, precise geographic coordinates of the cell tower location, and details about the city or region where the tower is situated. Analysis of this data yields insights in the density, distribution, and expansion of 5G networks.

Tower Maps: Tower Maps [17] offers proprietary data about cell tower locations across the globe. Each entry in this database includes specific details such as accurate location, tower height, construction date and site availability status. This dataset has been curated from data provided by over 600 cell tower companies for more than two decades. While the data does not explicitly differentiate between 4G and 5G support

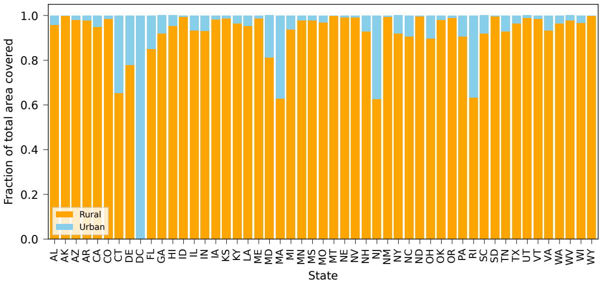


Figure 1: Fraction of rural and urban areas state wise.

for each tower, it provides important information about the distribution and characteristics of cellular infrastructure.

We utilize all three data sets because each on its own is not complete enough for our study. For instance, while the Tower Maps and Ookla 5G Map datasets offer more reliable location information of the physical cell tower infrastructure, the dataset does not indicate the number of individual cells the cell tower supports nor their radio types (e.g. 4G, 5G). This information is provided by OpenCellID. On the other hand, the location of the individual cells provided by OpenCellID is not precise; it is approximated using triangulation from crowdsourced measurements. Hence, we integrate the information in all three datasets to compile our understanding of mobile network connectivity and coverage.

2.4 Socioeconomic and Demographic Data

We utilize socioeconomic and demographic data sourced from the 2020 US Census [25]. This dataset provides extensive US data, including population density, household income, racial demographics, and broadband usage statistics. The Census Bureau also provides detailed classifications at the census block level, distinguishing between urban and rural areas, facilitating the examination and analysis of the spatial distribution of urban and rural areas across the country. Figure 1 shows the fraction of each US state covered by rural and urban areas. By integrating this dataset with network performance metrics obtained from Ookla's public data and the cell tower datasets from OpenCellID, Ookla and Tower Maps, we study the effect of factors such as area type and population density on broadband availability and quality across different US geographic regions, including census blocks, divisions, counties and states.

2.5 Dataset Integration and Challenges

Through analysis of the combination of these datasets, we seek to deepen our understanding of US cellular networks. The FCC's National Broadband Map measures cellular network availability through self-reported data from service providers and crowdsourced data from users. Integrating cellular deployment density data highlights the spatial distribution and capacity of existing cellular infrastructure, correlating availability with network performance to identify areas in need of investment. Demographic and socioeconomic data contextualize these findings, revealing how factors like area type and population density influence broadband availability and quality. This holistic approach enables data-driven decisions, supporting targeted investments, equitable policy initiatives, and efforts to ensure universal access to reliable high-speed mobile broadband services nationwide.

Table 1: Top and bottom five states by number of Speedtest tiles.

State	Speedtest Tiles	% of Total Speedtest Tiles	% of Total Tiles in State
Bottom 5			
DC	639	0.03%	32.6%
RI	4,662	0.21%	13.8%
HI	5,108	0.23%	5.8%
VT	5,641	0.26%	2.7%
DE	6,311	0.29%	13.1%
Top 5			
OH	93,051	4.23%	12.7%
MI	93,698	4.26%	3.64%
FL	110,960	5.04%	5.84%
CA	139,510	6.33%	3.4%
TX	186,461	8.47%	3.4%

One of the key challenges to our research is the lack of publicly available and granular ground truth data sources about mobile connectivity. This scarcity necessitates reliance on a variety of available datasets, each of which contributes a different partial piece to understanding the connectivity puzzle. Unfortunately, the datasets utilize different spatial indexing mechanisms and levels of spatial granularity, complicating the integration process. Moreover, cell tower and location datasets are primarily crowdsourced, which may compromise their completeness. Despite these challenges, we combine the datasets to create a cohesive framework for our research on mapping nationwide mobile connectivity.

3 OOKLA DATASET CHARACTERIZATION

We begin with a high-level characterization of the Ookla Speedtest dataset. The data from the 2021-2023 time period consists of approximately 7.6 million Speedtest data points with 2.2 million unique tiles across the US, with between 500k and 700k tiles recording Speedtests each quarter. To illustrate the extent to which each state is represented in the Speedtest dataset, Table 1 presents the five states with the highest and lowest numbers of unique Speedtest tiles during our study period, the proportion of these tiles relative to the total number of unique Speedtest tiles across all states in our dataset, and the proportion of these tiles relative to the total number of unique tiles within that state. There are a total of two to three million measurements taken every quarter for each of the three years, with the highest in 2021 Q1 (3.16M tests) and the lowest in 2023 Q4 (2.22M tests).

To analyze the distribution of these measurements, we begin by examining the number of Speedtests conducted and the number of unique Speedtest devices used per state, categorized by year and quarter. By normalizing these numbers against the population of each state, we obtain the density of test takers in each state. Our analysis reveals that Nevada, Arizona, and the state of Washington consistently rank in the top five states for both test density (number of tests taken per person) and device density (number of unique devices used per person) for each year and quarter from 2021 to 2023, with Nevada having the highest test density of 0.02 in Q4 of 2023. Conversely, Vermont, North and South Dakotas and Rhode Island consistently appear in the bottom five for the same metrics and time periods, with Vermont having the lowest test density of 0.002 in Q3 of 2023.

Next, to understand how much of the US is covered by the Speedtest data, we examine how many US census blocks have at least one Speedtest measurement during our study period. Our analysis reveals that out of 8.18 million census blocks, 17% are covered in the dataset. To examine the urban/rural distribution, we apply the US census bureau's urban-rural designation to census blocks. We assign each tile to a census block by calculating the centroid of the tile and identifying the corresponding census block in which it resides. While not error-free, this method provides a reasonable estimate for analyzing the area type distribution of the data. Our analysis reveals that 47% of the Speedtest tiles are from urban areas, while 53% are from rural regions. Of the total urban US census blocks, 17% have at least one Speedtest measurement recorded, and 19% of rural census blocks have at least one Speedtest measurement recorded. Our next step is to account for the number of times each tile appears in the data. We find that 65% of the Speedtest data is from urban areas, while only 35% is from rural regions. This distribution highlights the fact that while 763k rural and 674k urban census blocks appear in the Speedtest data, there is both a greater number and frequency of speed tests in urban areas. If aggregated at too large a geographic area, the urban dominance could skew the overall performance metrics and potentially mask rural broadband challenges and disparities.

We next analyze how well distributed the Speedtest measurements are between tiles. We find that 46% of the 7.6 million data points have only a single measurement recorded. Of these, 60% tiles are in rural census blocks, while 40% are in urban census blocks. To increase the representativeness of our analysis and decrease any skew from single tests, we filter out Speedtest tiles with only one measurement, leaving us with 4.08 million data points and 1.2 million unique Speedtest tiles. This data covers 943k census blocks, out of which 385k are rural and 558k are urban. This data is summarized in Table 2. As a final step, we compute the overall distribution of the Speedtest data across the US, as shown in Table 3. We provide this data as a baseline, and investigate the trends at more fine-grained spatial granularities in the following section.

Table 2: Summary of Ookla data in analysis.

Total coverage	Value
Data points	4.08 million
Tiles	1.2 million
Urban census blocks	558k (13.6% of US urban census blocks)
Rural census blocks	385k (9.4% of US rural census blocks)

Table 3: Summary of national performance metrics.

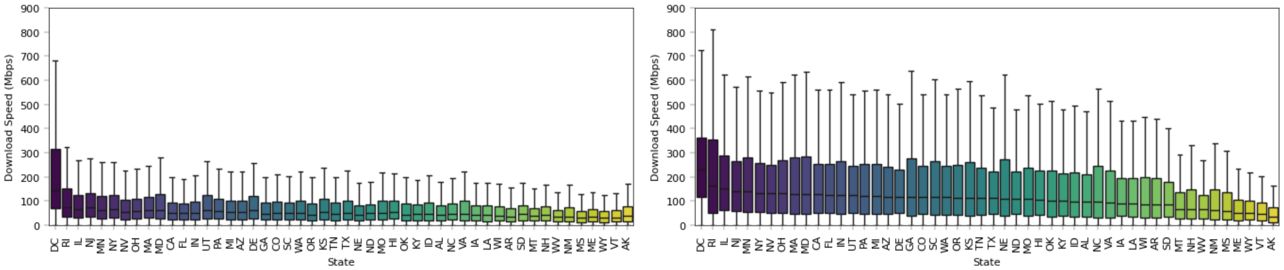
Metric	Median	Average	75^{th} Percentile	25^{th} Percentile
Download speed	72 Mbps	127 Mbps	164 Mbps	30 Mbps
Upload speed	11 Mbps	16 Mbps	23 Mbps	4 Mbps
Latency	32 ms	41 ms	45 ms	25 ms

4 MAPPING US CELLULAR NETWORKS

Our analysis is driven by two key research questions: (1) How have US cellular network performance metrics and coverage evolved? and (2) What is the relationship between cellular infrastructure density and measured Speedtest performance? We answer these questions through aggregation and analysis of the datasets described in Section 2. In short, we first assess how network performance metrics have evolved from 2021 to 2023, focusing on changes in download/upload speeds and latency across different geographic regions and spatial granularities. Due to the significant growth in 5G deployment and coverage during this time period, we also include a focused analysis of performance and deployment density in 5G coverage areas. Then, we examine whether cellular infrastructure, or in other words, cell towers and individual cells, correlates with network performance, and we examine its role in performance improvement/degradation.

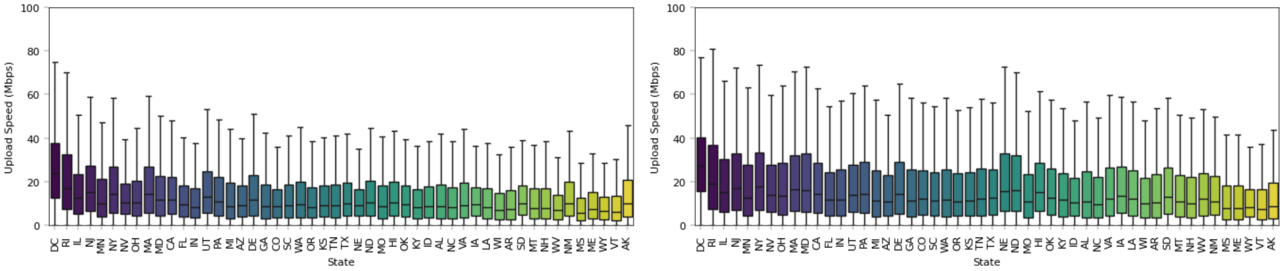
Question 1: How have US cellular network performance metrics and coverage evolved?

We begin with an analysis of the public aggregated Ookla Speedtest data from 2021 and 2023 by state, as shown in the box and whisker plots in Figure 2. In the figure, each box represents the interquartile range (IQR), which contains the



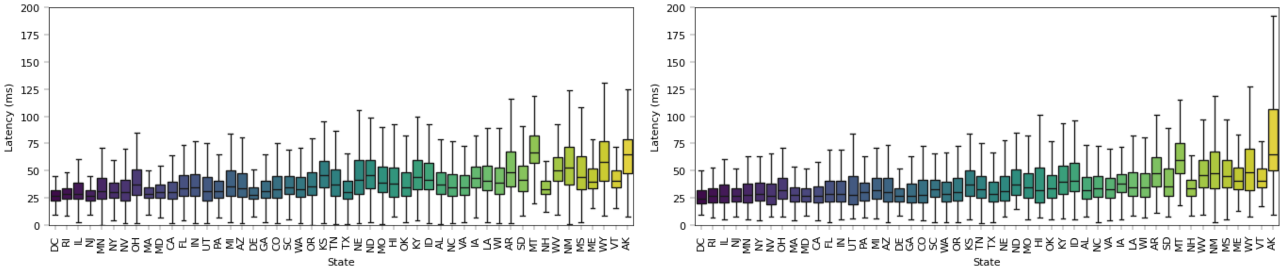
(a) Download speed - 2021

(b) Download speed - 2023



(c) Upload speed - 2021

(d) Upload speed - 2023



(e) Latency - 2021

(f) Latency - 2023

Figure 2: 2021 and 2023 distributions of aggregated performance metrics by state, ordered by decreasing 2023 median download speeds.

middle 50% of the data; the line inside the box denotes the median. The whiskers extend to the minimum and maximum values within 1.5 times the IQR from the quartiles, highlighting the range of the data; all points outside this range are considered outliers. The trends in Figure 2 clearly reflect an overall improvement in all three network performance metrics - download speed, upload speed and latency - across almost all states from 2021 to 2023. When we compare these metrics in 2021 and 2023, we find that the 75^{th} percentile download speed for all states was about 100 Mbps in 2021 but increased to to 300 Mbps in 2023. This improvement likely reflects the results of increased 5G deployment efforts during this time period [12].

To examine trends beyond the state-level geographic granularity, we group our Speedtest public data by region and by division, as designated by the Census Bureau [11] and shown in Table 4, and plot the yearly distributions of all network performance metrics. We present the findings for download speeds and confirm that the trends are similar for upload speeds and latency[2]. We present regional and divisional trends, as well as trends in tribal areas, for download speed in Figure 3. Figure 3 shows that there is consistent yearly improvement in network performance across all regions and divisions. Further, there is minimal difference in the distribution of performance metrics among the different

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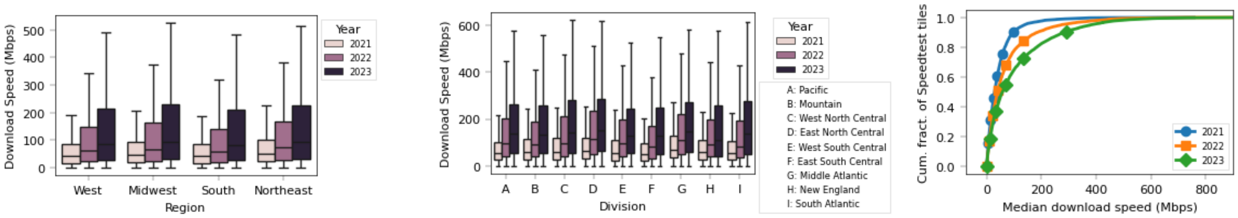
[2] In many cases, we focus the presentation of our results on download speeds because mobile internet usage predominantly involves activities such as online gaming, social media browsing, and video and music streaming, which are more download-intensive [22, 26]; further, download speeds have much wider variability than upload speeds and latency, making them a better indicator of network performance. In all cases, however, we confirm the trends are the same across all metrics, and highlight any inconsistencies.



(a) By region

(b) By division

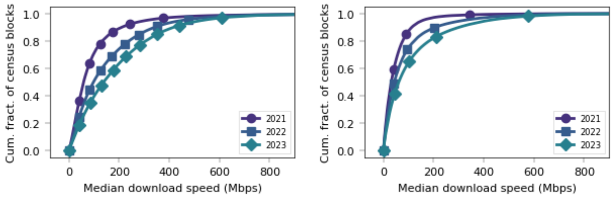
(c) Tribal areas

Figure 3: Yearly download speed aggregated by US Census Bureau region and division designations.

Table 4: US region, division, and state designations.

Region	Division	States
Northeast	New England	Connecticut, Massachusetts, New Hampshire, Rhode Island, Vermont, Maine
	Middle Atlantic	New Jersey, New York, Pennsylvania
Midwest	East North Central	Illinois, Indiana, Michigan, Ohio, Wisconsin
	West North Central	Iowa, Kansas, Minnesota, Missouri, Nebraska, North Dakota, South Dakota
South	South Atlantic	Delaware, Florida, Georgia, Maryland, North Carolina, South Carolina, Virginia, Washington, D.C., West Virginia
	East South Central	Alabama, Kentucky, Mississippi, Tennessee
	West South Central	Arkansas, Louisiana, Oklahoma, Texas
West	Mountain	Arizona, Colorado, Montana, Nevada, Idaho, Utah, New Mexico, Wyoming
	Pacific	Alaska, California, Hawaii, Oregon, Washington

regions when grouped by year, with less than 10 Mbps difference in their medians. While the results for our divisional analysis are consistent with the results from our regional analysis (i.e., there is no significant disparity in the network performance metrics across the different divisions), we observe that the Pacific, East North Central and the Middle Atlantic divisions show slightly better network performance metrics compared to the other regions in 2023. Within Tribal areas, there are 6,800 unique Speedtest tiles with at least two measurements in any quarter within the three year period. The median speed does not improve from 2021 to 2023, but the 80^{th} percentile speed doubles, from 100 Mbps to 200 Mbps.



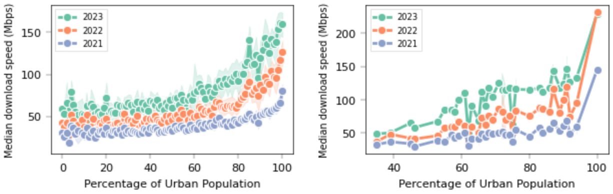
(a) Urban

(b) Rural

Figure 4: Relationship between census block type and download speeds by year.

Impact of urbanization on network performance. We next study performance differences in urban versus rural areas through the use of US Census Bureau designations at the census block level. To do so, we aggregate our Speedtest dataset over all census blocks by assigning tiles to corresponding census blocks, and we study the performance in urban and rural areas for each year from 2021 to 2023. We plot the cumulative distributions of the median download speeds in Figure 4. Consistent with our expectation, the median download speeds of urban areas outperform those of rural areas each year; urban areas in 2023 have the highest median speed of 200 Mbps, compared to only 75 Mbps in rural areas. Interestingly, the median speeds of urban areas in 2021 and rural areas in 2023 are almost equal, but the 80^{th} percentile speed of rural areas in 2023 is greater than that of urban areas in 2021. This indicates some growth in rural cellular deployments.

We next quantify the impact of urbanization on mobile network performance at the county and state levels by aggregating Speedtest tiles labelled urban (and rural) and computing the percentage of urban (and rural) census blocks at each of these granularities. We plot the median download speeds for each percentage value in Figure 5. As the percentage of urban population increases at the county level (Figure 5a), the median download speeds increase. Specifically, in 2023, median download speeds increase from 50 Mbps when the county is entirely rural to over 150 Mbps when the county is



(a) By county **(b) By state**

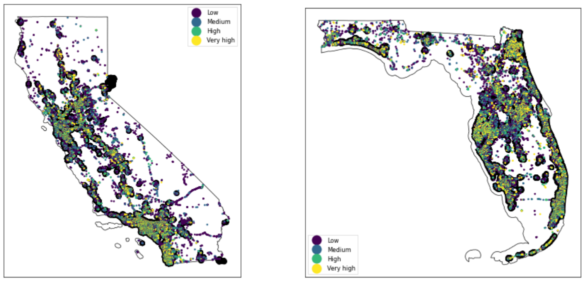
Figure 5: Relationship between percentage of urban population and download speeds.

entirely urban. We observe similar overall trends at a state level, as shown in Figure 5b.

As a case study, we overlay the download speeds from our data on the state wise Urban Areas map from the Census Bureau and show the plots for two example states, California and Florida, in Figure 6. Each point on the map represents the centroid of the Speedtest tile, color-coded by download speed categories based on the national percentiles: Low ($x < 25^{th}$ percentile), Medium ($25^{th} \leq x < 50^{th}$ percentile), High ($50^{th} \leq x < 75^{th}$ percentile), and Very High ($x \geq 75^{th}$ percentile). We observe that the urban centers exhibit a concentration of tests that consistently report higher download speeds compared to tests conducted in rural regions.

State wise performance changes. Our analysis indicates definitive improvements in mobile network performance from 2021 to 2023. To quantify these improvements and to understand discrepancies between states, we examine the percentage improvement in median download speed, upload speed and latency metrics from the first quarter of 2021 to the last quarter of 2023 by state. We present our findings through chloropleth maps, as shown in Figure 7, to visualize these performance improvements and highlight areas that have made significant strides. We also plot the Q1 2021 median download speeds against Q4 2023 median download speeds, color-coded by the percentage improvements to highlight both the absolute and the relative improvements in Figure 8a.

Overall, we observe that the District of Columbia (DC) has the highest absolute value across all three network performance metrics in both 2021 and 2023, but Nebraska (NE) showed the greatest relative improvement for all metrics; Nebraska's median download speed increased by over 350% (from 50 Mbps to 225 Mbps), upload speed increased by over 75% (from 12 Mbps to 20 Mbps), and latency decreased by over 30% (from 44 ms to 30 ms). At the other end of the spectrum, Alaska (AK), Maine (ME) and Vermont (VT) show minimal absolute and relative improvements across all metrics, suggesting the need for more targeted investments in these regions.



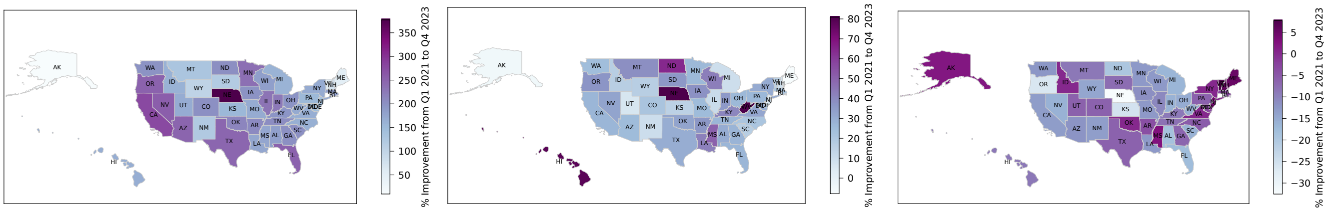
(a) California **(b) Florida**

Figure 6: Overlay of Speedtest download speeds on the Census Bureau's Urban Areas map.

To contextualize our findings further, we analyze the absolute and relative improvements in download speed separately for urban and rural areas and present the results by state in Figures 8b and 8c, respectively. While Nebraska shows the most increase in download speed overall, the speed increase is predominantly from urban areas, where it improves by over 400%. In rural areas, the increase is only 80%. On the other hand, West Virginia (WV) shows the greatest improvement in rural areas, with improvement of over 240%.

Location and Performance of Fast 5G. Due to the broad growth in 5G deployment during our study period, we conclude our analysis of Question 1 with an in-depth study of 5G growth and performance during this period. As discussed in Section 2, the US National Broadband Map provides detailed mobile broadband availability data, differentiating coverage by cellular technology, such as 3G, 4G LTE, and 5G. For our analysis, we include the Fast 5G H3 hexagons (hexagons labelled by the National Broadband Map to have a minimum speed requirement of 35/3 Mbps) representing coverage in both outdoor stationary environments and in-vehicle mobile environments. To compute the overall percentage coverage of Fast 5G in the US, which is mapped using the H3 index system, we begin by computing the total area of all Fast 5G hexagons. We find that approximately 30.9% of the US land area is covered by Fast 5G. Next, we associate each Fast 5G H3 hexagon with the census block(s) with which it overlaps, in order to estimate how many of the 8.18 million census blocks in the US intersect with at least one Fast 5G hexagon. Surprisingly, we find that, as of December 2023, approximately 86% of all US census blocks overlap with at least one Fast 5G hexagon, highlighting the widespread availability and reach of Fast 5G technology across the US.

To provide more context to this finding, we compute the total land area of all US urban and rural census blocks and the total land area of all urban and rural Fast 5G hexagons to determine the percentage of urban and rural areas covered by Fast 5G. We find that about 96% of all US urban land area

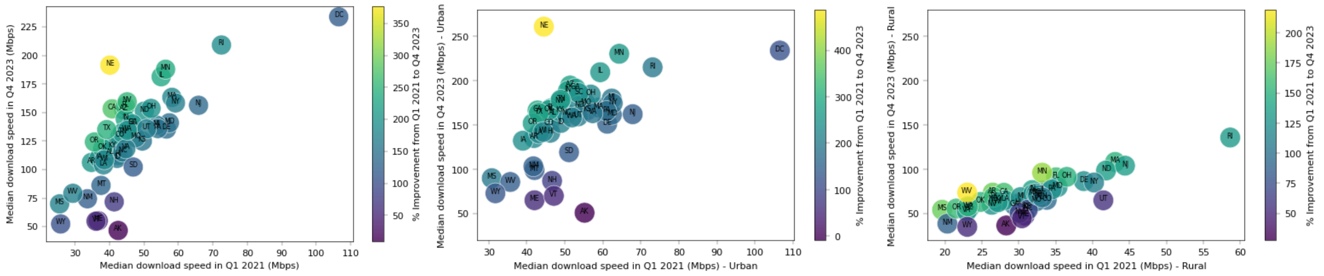


(a) Download speed

(b) Upload speed

(c) Latency

Figure 7: Percentage improvement in network performance metrics between Q1 2021 and Q4 2023.

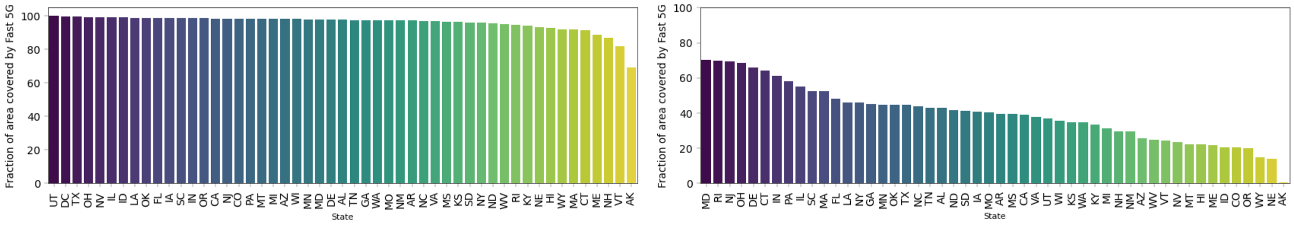


(a) Download speed - Overall

(b) Download speed - Urban

(c) Download speed - Rural

Figure 8: Relative improvement in download speeds from Q1 2021 to Q4 2023.



(a) Urban area covered

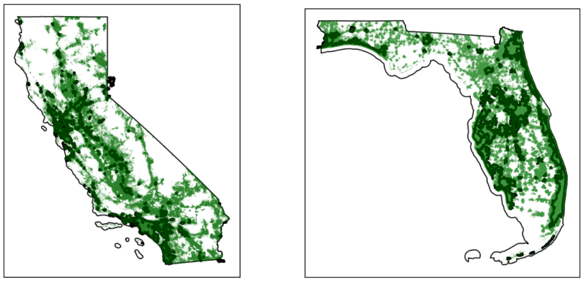
(b) Rural area covered

Figure 9: Rural and urban areas by state where Fast 5G is available according to the National Broadband Map.

is covered by Fast 5G, but for rural areas, only 30% is covered. This indicates that, despite the significant overlap with 86% of census blocks, the proportion of land area with meaningful coverage is significantly lower. Using this method, we then compute the coverage percentage by state for rural and urban areas separately and show the results in Figure 9. The majority of the urban areas in all states have some Fast 5G coverage; Utah (UT) has the highest coverage, at 96%, while Alaska (AK) has the lowest, at 64%. On the other hand, rural areas have much lower Fast 5G coverage; Maryland (MD) has the greatest value (72%) and Alaska (AK) has the least (less than 1%) coverage. We confirm that the results from our Fast 5G coverage analysis are consistent with FCC's newly released mobile broadband coverage data [23].

We visualize the distribution of Fast 5G coverage for two example states: California and Florida, in Figure 10. To create this image, we overlay the Fast 5G hexagons on the state map along with the Urban Areas map provided by the Census Bureau [18]. The figure shows that almost all urban areas and most rural areas in these states are covered by Fast 5G hexagons.

We note that the Fast 5G coverage data in Figures 9 and 10 are from the National Broadband Map, which reflects only the minimum speed available, as reported by ISPs. Therefore, we use Speedtest public data to analyze the performance of these Fast 5G hexagons to gain a more accurate understanding of 5G performance quality in areas designated as having Fast 5G availability. Of the 7.08 million census blocks identified to have some Fast 5G coverage, only 533,058, or



(a) California (b) Florida

Figure 10: Overlay of Fast 5G hexagons on the Census Bureau's Urban Areas map by state.

7.5%, are represented in the Ookla Speedtest data. We focus on this subset and analyze the 2023 data to measure Fast 5G performance. This reduction results in 650k Ookla total tiles, comprising 600k Fast 5G tiles and 50k non-Fast 5G tiles.

We plot the distribution of the three network performance metrics for both Fast 5G and non-Fast 5G tiles in Figure 11. We find that the tiles identified as Fast 5G exhibit notably superior performance. Specifically, the difference in median download speed, median upload speed and median latency are about 100 Mbps, 10 Mbps and 20 ms, respectively. Additionally, while the 20^{th} percentile download speed of Fast 5G is about 35 Mbps, the 80^{th} percentile reaches 500 Mbps, highlighting the massive capacity of Fast 5G networks. These results point to the need to reevaluate existing benchmarks, such as the minimum speed requirement of 35 Mbps, to effectively capture the capacity offered by this technology.

Key takeways: Our analysis reveals that US mobile network performance has significantly improved between 2021 and 2023, a timeline that coincides with significant growth in US 5G deployments [8, 9, 12, 15]. While there are not large performance differences among different US regions in the same year, performance does differ significantly by state. Some states show improvement of over 200% for download speeds, 80% for upload speeds and 40% for latency from 2021 to 2023, while there are also states where there is little to no improvement during this time period. Further, Vermont, Maine and New Hampshire actually show a 5% increase in latency while Alaska shows a 3% decrease in upload speeds and a 5% increase in latency. Finally, we broadly find that urban areas exhibit faster download speeds than rural areas and that, as urban population increases, network performance metrics tend to improve.

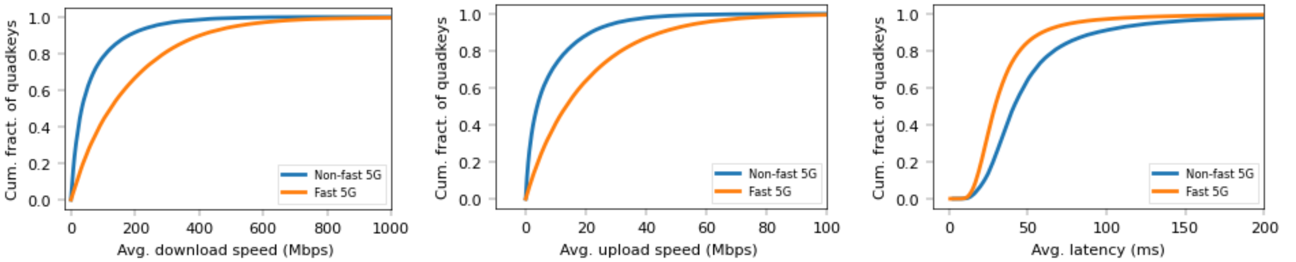
Question 2: What is the relationship between cellular infrastructure density and measured Speedtest performance?

Table 5: Percentage of cell towers and cells in rural and urban census blocks.

	Urban	Rural
Tower Maps (4G and 5G cell towers)	63.2%	36.7%
Ookla (5G cell towers)	54.1%	45.9%

Cellular deployment density is the number of cell towers per unit geographic area. As an indicator of criticality of cellular infrastructure, we examine the number of cell towers and individual cells, as well as the cellular deployment density, within a geographic region, and their relationship to measured cellular performance. To do so, we utilize the three cellular infrastructure datasets described in Section 2. Because cell towers represent physical infrastructure that can support multiple individual cells, we combine cell and cell tower datasets, utilizing multiple geographical aggregations, such as census blocks, counties, and states. These specific geographic granularities are chosen due to their relevance in policy-making, which typically targets these levels rather than spatial geometries such as square tiles or H3 hexagons. As we mention in Section 2, TowerMaps and Ookla provide tower datasets with precise location data, while OpenCellID offers cell location data derived from crowdsourcing and triangulation, accompanied by a range parameter indicating the variance in cell location accuracy within a specified radius, in meters. To combine datasets, we perform a spatial join using the geographic locations of the towers and cells with the designated geographic boundary. This spatial join allows us to associate each cell and cell tower data point with a specific geographic granularity, such as a county. Because census blocks require much finer spatial accuracy, we only utilize TowerMaps and Ookla datasets, due to their greater precision, for analysis at this level. At the county and state levels, we aggregate all three infrastructure datsets. We then analyze geographically co-located Speedtest data to uncover patterns in the relationship between cellular deployment and network performance.

Distribution of US cellular infrastructure: We begin by examining the distribution of cells and cell towers by state, focusing on the cellular deployment density, in Figure 12a (note the log scale on the y-axis). The cellular deployment density in Washington, D.C. is approximately 200 cells/km^2, which is a significant outlier from the other states, which are all in the 0.005 to 10 cell towers/km^2 range. To analyze the difference in cellular infrastructure between urban and rural areas, available at the census block level, we utilize the TowerMaps and Ookla cell tower datasets. Table 5 shows the number of cellular deployments by area type for these two datasets. We see that 64% of cell towers in the TowerMaps dataset are concentrated in urban census blocks, while 36%

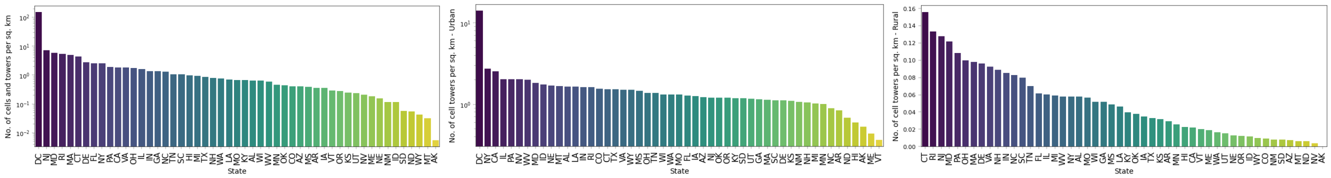


(a) Download speed

(b) Upload speed

(c) Latency

Figure 11: Median performance of Fast 5G vs. non-Fast 5G tiles nationwide.

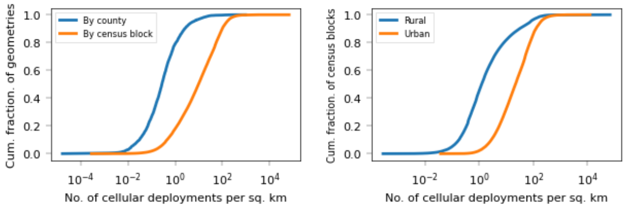


(a) Cellular deployment density

(b) Cellular deployment density - Urban

(c) Cellular deployment density - Rural

Figure 12: Distribution of cellular deployment density by state.



(a) By geometry

(b) By area type

Figure 13: Distribution of cellular deployment density by county and by census blocks.

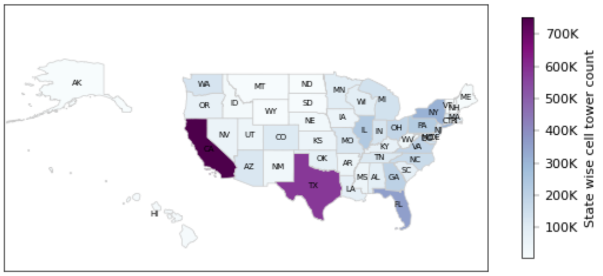
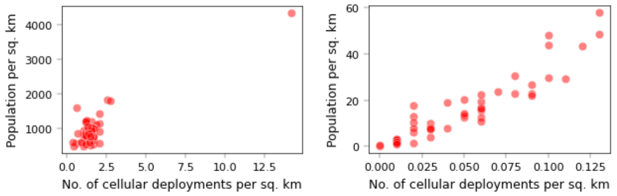


Figure 14: Number of cellular deployments by state.



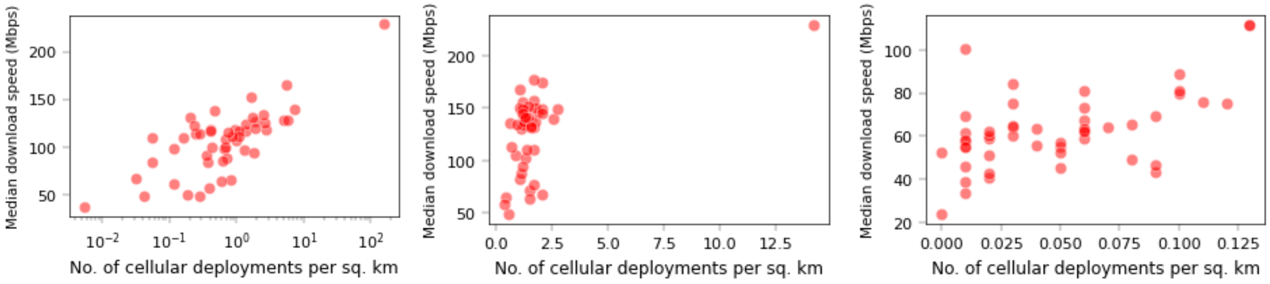
(a) Urban

(b) Rural

Figure 15: Relationship between cellular deployment density and population density by area type for each state.

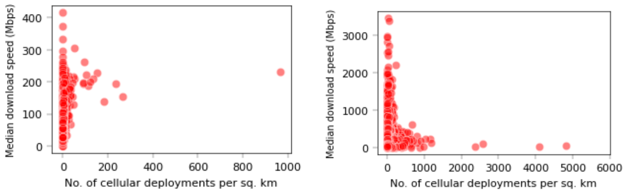
are from rural blocks. The 5G cell towers data from Ookla shows a smaller difference between urban and rural deployments, at 54% and 45%, respectively. We compute the cellular deployment density by state for urban and rural areas and present the findings in Figure 12b and 12c, respectively. While 90% of the states have an urban cellular deployment density greater than one (implying there is more than one cell tower per km^2), the highest density in rural areas is 0.16.

Next, we compute the cellular deployment density across all states aggregated at the county and census block levels and present the results in Figure 13a. We observe that the cell deployment density is significantly higher at the block level, with a median value of 8, than at the county level, with a median value of 0.1. We hypothesize that this is because of a higher concentration of cellular infrastructure deployments within smaller, densely populated urban regions, ensuring better coverage and capacity where it is most needed. To contextualize this finding, we compute the cellular deployment density for rural and urban census blocks separately and plot



(a) Download speed - Overall **(b) Download speed - Urban** **(c) Download speed - Rural**

Figure 16: Relationship between cellular deployment density and download speeds state wise.



(a) County level **(b) Census block level**

Figure 17: Relationship between cellular deployment density and download speeds.

the results in Figure 13b. We find that the density of cellular deployments in urban census blocks is significantly higher than that of rural census blocks, with median values over 10 times higher in urban blocks, confirming our hypothesis. In terms of the raw number of cellular deployments, shown in Figure 14, California, Texas, and Florida rank as the top three states, likely due to their large geographic areas and high populations.

Next, we analyze the relationship between cellular deployment density and population density for each state, separately for rural and urban areas, and show the results in Figure 15. We find that the relationship is strongly positive in both region types with a Pearson correlation coefficient[3] of 0.92 in rural areas and 0.88 in urban areas. This linear relationship suggests that as population density increases, cellular deployment density also increases, reflecting the direct influence of population density on cellular infrastructure deployment.

Impact of cellular deployment density on mobile network performance: We next explore whether variations in cellular infrastructure deployment correlate with differences in mobile network performance. To do so, we analyze the relationship between 2023 state wise network performance and cellular deployment density. For each state, we compute cellular deployment density by aggregating the number of cellular deployments (including both cell towers and individual cells) over the state area. We then calculate the median of the aggregated Speedtest network performance metrics for each state. The Pearson correlation coefficients between cellular deployment density and these median values reveal clear relationships: 0.56 for download speeds, 0.66 for upload speeds, and -0.20 for latency. This data is presented as a scatter plot for download speeds in Figure 16a, where each state is represented by a single data point; we confirm similar trends for upload speeds and latency. The correlations indicate that higher cellular deployment density is associated with improved download and upload speeds, and reduced latency, highlighting the significant, if unsurprising, role of infrastructure density in enhancing network performance. However, this relationship becomes less predictable at finer levels of granularity. At the county and census block levels, the cellular deployment density does not correlate linearly with the mobile network performance metrics, with correlation coefficients less than 0.1 for all three metrics. We show these findings for download speed in Figure 17. We hypothesize that this could be due to localized variations in demand and usage patterns, the type of cellular deployment, or other geographic and environmental factors, but we do not have the data to confirm our hypothesis.

Next, we analyze urban and rural areas in each state separately, and observe the correlation between cellular deployment density and network performance metrics; we present the findings for download speeds in Figures 16b and 16c, respectively. In rural areas, higher deployment density shows a moderately strong positive correlation with download speeds (0.6), a moderate positive correlation with upload speeds (0.42), and a moderate inverse correlation with latency (-0.54). This indicates that higher deployment density in rural areas generally improves mobile network performance metrics. In urban areas, download speeds have a moderate positive

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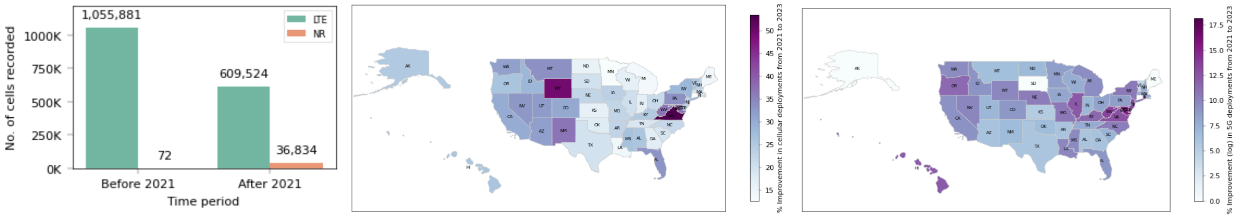
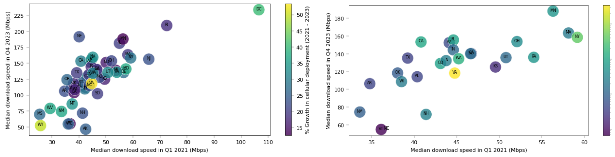
[3] The Pearson correlation coefficient measures the linear relationship between two variables and ranges from -1 to 1, where 1 indicates a perfect positive relationship, -1 a perfect negative relationship, and 0 no linear relationship.



(a) Number of new cells recorded **(b) Cell density change - Overall** **(c) Cell density change - 5G**

Figure 18: Increase in number and density of cell deployments from 2021 to 2023 by state.



(a) 4G and 5G cells combined **(b) 5G cells**

Figure 19: Relationship between network performance improvements and percentage increase of cell density from 2021 to 2023.

correlation with deployment density (0.48), upload speeds show a moderate to strong positive correlation (0.71), and latency has a weak inverse positive correlation (-0.22). This indicates that while higher deployment density in urban areas generally improves network performance metrics, there could be other localized factors that affect performance in these regions.

Growth in cellular deployment: Of the three cellular infrastructure deployment datasets we utilize, only the OpenCellID dataset includes “created” and “updated” dates for each cell, indicating when the cell was first added to the OpenCellID database and when it was last seen, respectively. Since we do not have ground truth about when cellular infrastructure was deployed, we use the date on which a cell first appeared in the database as an approximation of the date it was deployed. Using this method, we identify cells deployed before 2021 and those deployed in Q1 2021 or later to observe growth over time. From 2021 to 2023, 610k new 4G cells and 37k new 5G cells were observed in the dataset. Specifically, the number of 5G cell deployments increased 540 times between 2021 and 2023, from only 72 in 2021 to approximately 36,900 by 2023, as shown in Figure 18a. We examine changes in cellular deployment density from 2021 to 2023 in Figures 18b and 18c. Overall, we find that Wyoming and Virginia experience the largest percentage increase in cellular deployment density, exceeding 50%. For 5G, the northeastern states exhibit the highest growth rates.

Relationship between infrastructure growth and measured performance: We conclude our analysis by examining how growth in cellular deployment correlates with measured mobile network performance. We would expect that an increase in cellular deployment density would lead to an improvement in network performance, but interestingly we find that while nearly every state shows an improvement in all network performance metrics from 2021 to 2023 and also has an increase in the cellular deployment density, the percentage increase in overall deployment density does not necessarily correlate with the performance increase (correlation coefficient of -0.14 overall and -0.13 for 5G with download speeds). We present these findings for download speeds in the form of scatter plots for 4G and 5G cells combined in Figure 19a and for 5G specifically in Figure 19b, and confirm that the trends hold for upload speed and latency metrics. This lack of correlation could be attributed to factors such as differences in population distribution, balance between rural and urban areas, backhaul infrastructure, user demand, and other localized variations that may affect the relationship between deployment density and performance improvements.

Key takeaways: In summary, we find that the relationship between cellular deployment density and cellular network performance is moderately positive and linear: an increase in cellular deployment density is associated with a 56% increase in median download speeds, a 66% increase in median upload speeds, and a 20% reduction in latency at the state level; however, at more granular geographies, this does not hold true. Additionally, urban areas exhibit 15 to 40 times higher cellular deployment density compared to rural areas. Finally, we find that despite the overall positive trends between cellular deployment density and mobile network performance, the weak correlation between increases in deployment density and performance improvements suggests that other factors also influence performance. More granular data on cellular technology and deployment dates would enable a more thorough analysis of these factors and support more targeted policy investments.

5 RELATED WORK

A variety of prior studies have effectively utilized crowdsourced speed test data to measure broadband performance. For example, the work in [37] and Ookla's own reports [39] have demonstrated how such data can be used to assess digital inequities and broadband performance across various regions. Ookla Speedtest measurements were used to compare cellular and WiFi performance in [42], while Canadi et al. [29] benchmarked Internet performance across metropolitan areas using speed tests. These studies underscore the importance of contextualizing speed test data for accurate interpretation, as also highlighted in [30, 32, 35, 40].

On the topic of mobile broadband, the authors of [27] described the status of mobile broadband testing efforts and highlight the challenges in measuring mobile broadband performance. Analysis of mobile access bandwidth for millions of users emphasized the interdependence of different cellular technologies [44]. Moreover, other studies have investigated the impact of device parameters and signal strength on mobile Internet quality of experience and latency [31, 43].

From a policy perspective, prior work has mapped connectivity and explored the implications of broadband access policies. For instance, the discrepancies in the FCC's broadband availability reports and their overestimation of Internet access in marginalized communities were critically examined in various works [28, 33, 36, 38]. Analysis of Ookla Speedtest data explored regional sampling bias and the relationship between Internet performance and demographic variables, stressing the need for addressing these biases in policy frameworks [34].

6 CONCLUSION

Our work aims to provide a longitudinal analysis of the evolution of cellular network performance and the criticality of cellular infrastructure deployment in the US. We highlight key trends and relationships with factors such as regional variations, variation by area type (urban vs. rural), and cellular deployment density. Our analysis indicates that, from 2021 to 2023, measured cellular performance improved across almost all US states and regions. Urban areas continue to outperform rural areas, and cell density in urban regions is 15 to 40 times higher than in rural regions. This gap aligns with population density, reflecting the expected relationship between infrastructure deployment and population distribution.

The precision of our study could be enhanced by more detailed location data, radio type specifics, and deployment dates of cellular infrastructure. Such data would also greatly benefit policymakers by allowing for more targeted investments and a precise analysis at finer spatial granularities to understand how performance improvements relate to deployment growth. Additionally, because Fast 5G networks achieve median download speeds up to 200 Mbps, the current 35/3 Mbps benchmark is inadequate. Updated performance criteria are recommended to better capture the advancements in 5G technology.

7 ACKNOWLEDGMENTS

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