

5G Metamorphosis: A Longitudinal Study of 5G Performance from the Beginning

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Abstract

The cellular network has undergone rapid progress since its inception in 1980s. While rapid iteration of newer generations of cellular technology plays a key role in this evolution, the incremental and eventually wide deployment of every new technology generation also plays a vital role in delivering the promised performance improvement. In this work, we conduct the first *metamorphosis* study of a cellular network generation, 5G, by measuring the user-experienced 5G performance from 5G network's birth (initial deployment) to maturity (steady state). By analyzing a 4-year 5G performance trace of 2.65M+ Ookla® Speedtest Intelligence® measurements collected in 9 cities in the United States and Europe from January 2020 to December 2023, we unveil the detailed evolution of 5G coverage, throughput, and latency at the quarterly granularity, compare the performance diversity across the 9 representative cities, and gain insights into compounding factors that affect user-experienced 5G performance, such as adoption of 5G devices and the load on the 5G network. Our study uncovers the typical life-cycle of a new cellular technology generation as it undergoes its "growing pain" towards delivering its promised QoE over the previous technology generation.

CCS Concepts

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

Keywords

5G, Measurement, Coverage, Network Performance

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1 Introduction

The cellular network has undergone rapid progress since its inception in the 1980s, with five generations of cellular technology over the past 45 years, each spanning roughly a decade. The most recent generation, 5G, which was rolled out in 2019, promises ultra-high bandwidth and ultra-low latency, far surpassing the performance of 4G LTE, via a combination of PHY layer innovations such as higher frequency bands, higher order modulation, beamforming, (massive) MIMO, and wider channels. Such high data rates, combined with low latency, hold the promise to finally support the new class of bandwidth-intensive, latency-critical applications such as Augment Reality (AR) and Mixed Reality (XR) [23, 24, 26, 30], Connected Autonomous Vehicles (CAVs) [27, 49], and the Metaverse, often dubbed as 5G "killer" apps.

While the rapid iteration of cellular technology generations drives progress, the incremental and eventual widespread deployment of each new generation is equally critical to achieving the promised performance improvements. Beyond the gradual rollout of carrier infrastructure, advanced features (e.g., carrier aggregation in LTE) are also introduced incrementally, with deployment timelines varying across carriers and countries.

This pattern is particularly evident in 5G, where most carriers initially adopted Non-Standalone (NSA) mode to accelerate time to market – using 5G for data-plane operations while retaining existing 4G infrastructure for control-plane operations – before gradually upgrading to Standalone (SA) mode.¹ Meanwhile, many performance-enhancing features, such as carrier aggregation up to 8 component carriers (CC) in mmWave bands and aggregation across TDD and FDD midbands, are being rolled out incrementally and are supported only by newer devices and 5G chipsets. As a result, user experience with 5G can vary widely across different stages of the technology's lifecycle.

These observations motivate the need for a comprehensive evaluation of 5G performance from its initial deployment to maturity. Such a longitudinal study can provide valuable insights into the network's evolution – including coverage expansion, throughput growth, and latency reduction – as operators deploy new infrastructure and roll out new features over time. In addition, this type of study can help bridge the gap between the technical promises of the 5G standard and the real-world experience of everyday users, offering a grounded perspective on user-perceived performance. Observing the network from early deployment through maturity

¹In the US, 2 out of 3 major carriers still supported only NSA through 2024.

across diverse locations can uncover meaningful differences in performance between operators and regions. These insights can inform policymakers and researchers in shaping regulatory strategies and guiding the design of both current and future network deployments.

Despite of the importance of studying the evolution of 5G performance, the large body of measurement studies conducted over the past 5 years [6, 7, 10, 11, 13–17, 22, 25, 31–36, 41, 42, 46–48] remains limited in terms of time span, geographic scope, or both, and provides only a fragmented snapshot of user-perceived performance at specific points in time and space. To the best of our knowledge, no prior work has systematically examined the evolution of 5G – or any other cellular technology – across its entire lifecycle, from initial rollout to maturity.

This work fills this gap by conducting the first *metamorphosis* study of a cellular network generation – 5G. We analyze a 4-year (from January 2020 to December 2023) dataset of 2.65+ million Ookla® Speedtest Intelligence® measurements over cellular networks collected in 9 cities from the US and EU to explore the technology coverage and user-experienced 5G performance from 5G network's birth (initial deployment) to maturity (steady state). Past work [12, 28, 37, 39, 43] has shown that, although crowdsourced speed test measurements may contain biases due to their uncontrolled collection, they are a rich source of "in-the-wild" network performance data. Our study unveils the detailed evolution of 5G coverage, throughput, and latency at the quarterly granularity while contrasting 5G against the mature 4G technology, compares the performance diversity and evolution across the 9 representative cities and across major cellular carriers in each city, and provides insights into compounding factors that affect user-experienced 5G performance, such as the adoption of 5G devices and the load on the 5G network. Our main findings are summarized as follows:

- The overall 5G coverage has evolved over 4 phases: slow growth, rapid growth, a second slow growth, and stability (maturity). Individual US cities follow the overall trend, whereas EU cities exhibit a slower "rapid growth" phase, and have a continued "second slow growth" phase instead of a stable period. Different operators in each city make independent choices of when to roll out their 5G services and at what rate, with some EU operators delaying their 5G rollout till the first quarter of 2022.
- The overall user-experienced 5G downlink throughput has also evolved over 4 phases – high 95th percentile, increasing median, stable median, and a second increasing median. However, these four phases do not align with the four coverage phases. On the other hand, the 5G uplink throughput has largely remained the same throughout the entire 4-year period. While the downlink throughput of US cities follows the same 4 phases, the EU cities diverge in the last phase and instead show either a stable or decreasing median. Comparing operators in each city, the operators with the highest 5G coverage do not necessarily have the highest throughput.
- The overall 5G latency exhibits a decreasing trend starting in mid 2022, while it always remains lower than the 4G median latency. The latency trends across different cities are much more varied compared to the overall 5G latency trend.

Overall, our study uncovers the lifecycle of the latest cellular technology generation, 5G, as it undergoes its "growing pains" toward delivering its promised QoE improvements over the previous generation.

2 Related Work

Crowdsourced measurement studies. There have been several studies based on datasets collected from crowdsourcing apps such as Ookla Speedtest and M-Labs [5, 28, 37–39]. These studies focus on broadband Internet performance and examine aspects such as Internet access inequities, the existence of bias, and the importance of contextualization in crowdsourced datasets. In contrast, our work focuses on the evolution of a specific cellular technology.

Measurement studies of older cellular technologies. Previous studies have measured the performance of 3G and 4G networks using crowdsourced measurements from either commercial or custom-built apps [4, 8, 9, 20, 29, 40, 43, 45]. All these works have a limited time span of at most a few months and none of them focuses on the metamorphosis or life-cycle of a technology generation.

5G performance studies. Since its initial roll-out in 2019, numerous studies have evaluated various aspects of 5G performance [6, 7, 10, 11, 13–17, 22, 25, 31–36, 41, 42, 46–48], but most are limited in geographic scope, focusing on one [6, 15, 25, 31, 33–35, 46] or a few cities [11, 17, 32, 41, 42]. While these studies provide valuable insights into 5G performance within localized areas, they may not necessarily reflect worldwide performance trends. Additionally, these studies generally cover short time spans, from a few days to weeks [11, 14, 16, 17, 32–35, 41, 42, 46], and do not track performance evolution over time. Moreover, the majority of these studies focus primarily on downlink performance, with only a few exceptions [7, 16, 17, 22].

Some studies cover broader geographic regions [7, 10, 13, 14, 16, 19, 21, 36, 48], but are based on short campaigns, which have limited long-term insights. For example, the work in [36] studies the evolution of 5G performance from a mobile operator perspective over a 3-year period, but it uses a dataset spanning 3 weeks in 2020 and one week in 2022, which only offers two snapshots of the observed performance during the 3-year period. A few other works conduct long-term studies, but are confined to a single city [15, 25]. The three works closest to ours are those in [22, 44, 47]. The work in [22] studies 5G uplink performance across 8 cities in North America and Europe, using measurements from 1-2 recruited volunteers in each city over a 14-month period, focusing on the mature phase of 5G (2022-2023). In contrast, our work uses 2.65+ million Ookla Speedtest spanning 48 months. The work in [47] uses a crowdsourcing app, similar to Ookla Speedtest, to collect a large 5G performance dataset over a 2-year period in China. The period under study is 2020-2021, i.e., it only covers the initial 5G deployment phase. Finally, the work in [44], analyzes a dataset of 1.75 million Ookla Speedtest Intelligence measurements over 3 years and 8 U.S. cities. However, unlike our work, it focuses on the impact of network and device features on 5G performance and does not perform a longitudinal or cross-sectional study.

To our best knowledge, our work is the first to perform a metamorphosis study of a cellular network technology generation, i.e., a longitudinal and cross-sectional measurement campaign of the 5G network from initial to mature deployment.

3 Ookla Measurement Methodology

Ookla relies on consumers to conduct a Speedtest that primarily measures downlink TCP throughput, uplink TCP throughput, and

latency. Each test log in the dataset includes over 100 fields, including measured downlink throughput, uplink throughput, and latency, geographic coordinates, time of the test, server location, type of server (auto- or user-selected), access technology, device OS, device network chipset, network operator, and cell ID (in the case of tests over cellular networks). Details about the measurement methodology can be found in [1].

Each end-user runs the Speedtest client on either mobile devices (Android/iOS) or through web browsers on desktops/laptops. The network access technology can be Ethernet, WiFi, or cellular. For our analysis, we focus only on the measurements that were conducted on smartphones/tablets over cellular technologies (LTE/5G).

On each device, the tests are run in the foreground using a client-server testing engine that scales the number of TCP connections, in order to saturate and accurately measure client-side connections up to 10 Gbps. This allows measuring the full extent of the real-world performance of ultra-fast connection technologies such as 5G.

To facilitate latency measurements, Ookla operates a vast testing infrastructure of over 15,000 servers worldwide [3]. Distant servers can increase latency and additional bottlenecks, hence the Speedtest app selects by default a server geographically close to the user's location with the least round-trip latency for each test. The app also allows users to select any server of their desire, however, for our analysis, we focus only on those measurements where the server was auto-selected.

Past work [12, 28, 37, 39, 43] has noted that, due to their uncontrolled collection, crowdsourced measurements may introduce bias in terms of the network conditions under which tests are conducted and the locations where they originate. Although we acknowledge the potential for such bias in our dataset, it is difficult to quantify to what extent it affects our findings. For example, prior studies [12, 43] argue that users typically run speed tests under poor network operating conditions. However, our results show median downlink throughputs of a few 100s of Mbps in all 9 cities and even 25-th percentiles above 100 Mbps in several cities – suggesting that this assumption does not universally hold. According to Ookla, although testing under poor conditions is a common motivation, it is not necessarily the dominant one. Users also frequently run Speedtest when arriving at an unfamiliar location, seeking to assess network performance in a new environment or under crowded conditions. Additionally, many tests are driven by curiosity – whether to gauge expected connectivity at a specific location or time, or to evaluate a new technology. This last use case is particularly relevant for our dataset, which includes measurements over a new cellular technology (5G), and is supported by our results in §5.2 and §6.2.

Another potential source of bias in the case of cellular measurements is the presence of roaming users, who may be offered lower speeds in "Visited Networks". However, the fraction of tests under roaming out of the total number of tests in our dataset is very small (ranging from 0.63% in Indianapolis to 5.55% in Dusseldorf), and we believe that it has a negligible impact on our overall results.

4 Overall Statistics

We analyzed 2.65+ million Ookla Speedtest Intelligence measurements from 9 cities (4 US cities and 5 EU cities), over a 4-year period from January 2020 to December 2023. Since Ookla does not share

Table 1: Overview of Ookla dataset.

City	Test count	% NR tests	Operator count	Cell ID count	Rad. of gyration (km)
Boston	365,656	44%	488	1360	4.06
Indianapolis	94,742	49%	133	1448	10.61
Miami	462,215	36%	620	1287	3.22
Portland	322,388	43%	260	1296	5.74
Geneva	95,868	32%	250	886	1.45
Lausanne	126,969	28%	143	833	2.01
Dresden	104,909	28%	186	1047	4.66
Düsseldorf	342,719	28%	447	1318	4.36
Oslo	473,867	29%	484	1355	4.65
Total	2,658,653	37%	3011	10831	

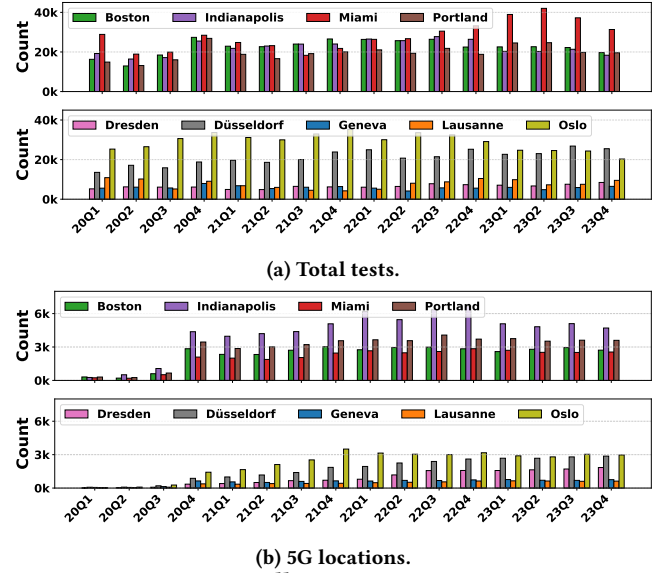


Figure 1: Overall measurement statistics.

data from big urban centers, we selected medium-sized cities from diverse geographic regions, covering both US and Europe. For example, in the US, we selected cities from the East Coast, West Coast, and Midwest. We also chose two cities from the same country in two cases in Europe (Germany and Switzerland) for a comparison of the trends between cities in the same country. Table 1 summarizes our dataset, listing for each city the total number of tests, the percentage of these tests over 5G, the number of operators included in the tests, the number of distinct Cell IDs, and their geographic spread (expressed as the radius of gyration [18]). Note that, although the operator count is very high in each city, approximately 85% of the tests in each city come from its top 3 operators. Also note that a city does not include its vicinity regions, i.e., the metropolitan region, e.g., Boston refers to the city of Boston, not Greater Boston.

The dataset's time scale has been consolidated into quarters to facilitate statistical analysis, resulting in 16 quarters, from Q1 2020 to Q4 2023. The number of tests per quarter for each city are shown in Fig. 1a. The 4 US cities have a minimum of 17K tests and a maximum of 43K tests each in a single quarter. Of the 5 EU cities, Lausanne, Dresden, and Geneva have a min and a max of 4K and 12K tests each over each quarter, while Düsseldorf and Oslo have a min and max of 14K and 35K tests each over each quarter. With each test contributing one sample of the metric being measured,

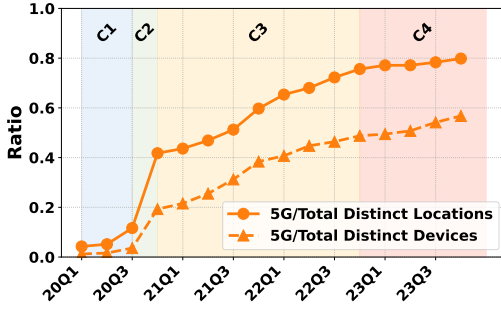


Figure 2: Evolution of quarterly 5G coverage ratio and device ratio over 4 phases (C1 – C4).

the high number of tests in Fig. 1a shows that each quarter in every city has statistically significant data.

Another key aspect of the measurement data is the extent of 5G deployment within a city. This can be assessed by identifying the distinct locations where 5G tests were conducted. To facilitate this analysis, all tests are grouped by test locations (latitude and longitude pairs) within each quarter. Given that location information in the dataset is rounded to three decimal points, this results in an evenly spaced grid of locations, approximately 100 meters apart. If at least one test at a location was performed over 5G, that location is marked as a *5G location*. Looking at Fig. 1b, we observe a low count of 5G locations in the first three quarters (Q1–Q3 2020), which is somewhat expected, given that 5G deployment was in its early stages. This can be further attributed to a combination of factors: (i) a limited number of users with 5G-capable devices and (ii) reduced mobility due to COVID-19 restrictions. By the end of the period, however, the final count of 5G locations shows a substantial number of tests across all cities.

5 Overall Longitudinal Analysis

We start by analyzing the overall evolution of 5G coverage and user-experienced performance over the 4-year period, from the initial deployment to mature deployment, by combining the measurement data from all the cities.

5.1 Coverage

To illustrate the 5G coverage trend over the four years, we plot the *5G coverage ratio*, defined as the ratio of distinct 5G locations to the total distinct locations (including both LTE and 5G coverage) for all cities combined, on a quarterly basis. To examine any correlation with device penetration, the same plot also includes the *5G device ratio*: the ratio of distinct 5G-capable devices to the total distinct devices (LTE and 5G) in the dataset.

Fig. 2 shows that the growth of 5G coverage ratio has gone through 4 phases: **C1** from 2020 Q1 to 2020 Q3 – we observe a minimal coverage ratio but with a slightly increasing trend, which can be attributed to a low number of distinct 5G devices for the reasons mentioned in §4. **C2** from Q3 to Q4 2020 – a substantial increase in 5G coverage ratio occurs here, likely tied to the release of the first 5G-capable iPhone (iPhone 12) at the beginning of Q4 2020, which boosted the number of 5G-device ratios as well. **C3** from Q4 of 2020 to 2022 Q4 – we observe a general trend of 5G coverage ratio steadily increasing, by about 5% per quarter. **C4**

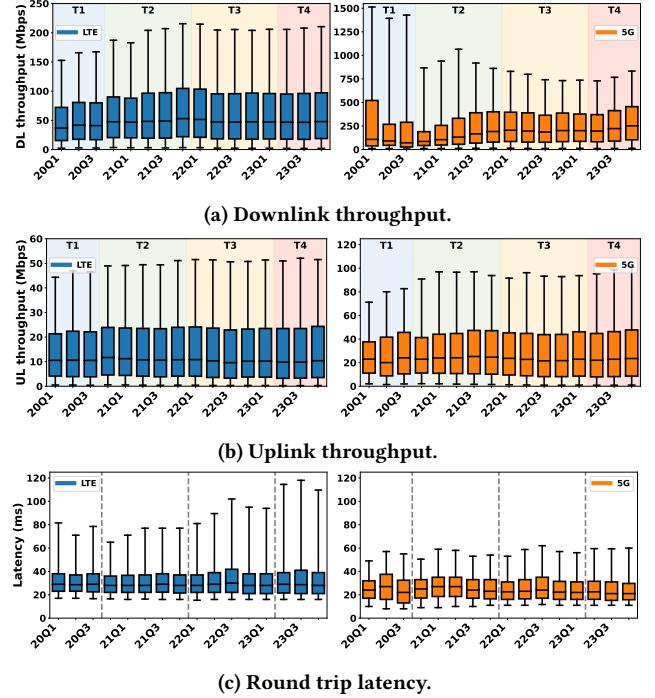


Figure 3: Evolution of quarterly throughput and latency over 4 phases (T1 – T4).

2022 Q4 onwards – we observe a stable state with the 5G coverage ratio only increasing by a total of 4% over 4 quarters, in spite of a continuously increasing trend in the number of 5G capable devices, suggesting that the deployment of 5G equipment by operators has reached a mature stage at these 9 cities by 2022 Q4.

5.2 Throughput

Figs. 3a, 3b show boxplots of the overall downlink and uplink throughput evolution, respectively, for both LTE and 5G, where each location contributes a single throughput value i.e., the mean of throughput values at each grid point location is taken before calculating the percentiles. The whiskers in Figs. 3a, 3b and all the following figures denote the 5th and 95th percentile. We removed outliers for better visual clarity. We make the following observations.

(i) 5G downlink throughput (Fig. 3a, right) can also be divided into 4 phases, but these 4 phases are not the same as the coverage phases in Fig. 2.

T1: The first phase, 2020 Q1 to 2020 Q3, is characterized by low median throughput but a notably high 95th percentile throughput (contributed by the traces from US cities). This trend likely reflects the initial excitement around 5G deployment: while the infrastructure was still limited, users actively sought out high-band (mmWave) towers in the US to experience peak speeds. During this phase, the median throughput ranges from 70 to 100 Mbps.

T2: The second phase, 2020 Q4 to 2021 Q4, is characterized by an increasing median throughput trend, from 80 Mbps to 190 Mbps. The 95-th percentiles in **T2** are significantly lower than in **T1** and show an increasing trend only during the first three quarters and a decreasing trend afterward. We speculate that the reason for

the throughput increase is two-fold: the number of 5G capable devices increases (Fig. 2) and operators increase/improve their 5G infrastructure with more focus on the mid and low bands. The initial excitement of 5G has also worn and that may be the reason for the lower 95th percentile drops in comparison to phase **T1**.

T3: The third phase, *2022 Q1 to 2023 Q1*, is a phase of stability. The median throughput here lies in the tight range of 185 to 205 Mbps, with no particular trend. The 95th percentiles are further reduced compared to **T2**. This period of stability points to a shift in focus from improving performance to further extending the infrastructure (see Fig. 2).

T4: The fourth phase, *2023 Q2 to 2023 Q4*, exhibits again an increasing median throughput trend, from 200 Mbps in 2023 Q2 to 250 Mbps in 2023 Q4. Unlike in **T2**, the 95th percentiles also exhibit a similar increasing trend in the period. This period suggests that the focus has shifted back to improving performance, with some operators (e.g., T-Mobile in the US) extending their SA coverage and enabling new features (e.g., 4 carrier aggregation in the midbands), while newer phones also support these new features.

(ii) In contrast to 5G downlink throughput, 5G uplink throughput (Fig. 3b, right), which is an order of magnitude lower than the downlink throughput, does not exhibit any visible trend, except for an increasing trend of the 95th percentile in the first 5 quarters. This trend is very different from the trend observed for the downlink 95th percentiles in Fig. 3a. In phase **T1**, the median uplink throughput goes up and down between 20 and 25 Mbps, while during **T2**, **T3**, and **T4**, the median throughput varies by 1-2 Mbps across quarters; between 23 and 25 Mbps in **T2**, 22-24 Mbps in **T3**, and 22-23 Mbps in **T4**.

(iii) LTE downlink throughput (Fig. 3a, left) remains mostly stable, but it can also be divided into two phases – one combining throughput in **T1** & **T2** and one combining **T3** & **T4**. During **T1** & **T2**, we observe an increasing trend for the median throughput, from 35 Mbps to 50 Mbps, and a more pronounced increasing trend for the 95th percentile throughput, suggesting that operators kept improving LTE performance during this period while also deploying their 5G infrastructure. During phases **T3** & **T4**, we observe a slight decrease in the median throughput from 50 to 45 Mbps by 2022 Q3 and afterward, the median throughput remains stable at 45 Mbps. During this period, the focus has clearly shifted from LTE to 5G.

(iv) Similarly, LTE uplink throughput (Fig. 3b, left) exhibits no overall trend except for an increasing trend for the 95th percentile in the first 4 quarters. Similar to 5G uplink throughput, the median LTE uplink throughput remains stable during the 4 years in a tight range of 10-11 Mbps.

Comparing the median LTE and 5G throughputs in Figs. 3a, 3b, we observe that the 5G downlink median values are 2x higher than the LTE median values during phases **T1** and **T2** and become 4x higher during phases **T3** and **T4**. The uplink 5G median values remain 2x higher than the LTE median values during the complete 4-year period.

5.3 Latency

Fig. 3c shows the evolution of LTE and 5G round trip latency. Looking at the 5G latency (Fig. 3c, right), we observe that the latency

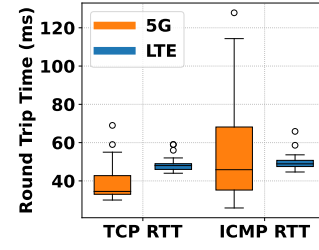


Figure 4: Latency comparison with different measurement methods.

does not exhibit drastic changes over the 4-year period. The 5th-to-95th percentile range in every quarter is about 40-50 ms, whereas the median latency has a range of 21-28 ms. Nonetheless, a closer look reveals a pattern of increasing and decreasing periods: an increase during the first half of phase **T2**, followed by a decreasing trend in the second half, and a similar pattern for the two halves of phase **T3**, with the decreasing trend continuing during phase **T4**.

Fig. 3c left shows that for LTE latency, the 95th percentile latency has a generally increasing trend while the median latency remains fairly stable, ~29 ms across all quarters.

Impact of latency measurement methodology. When we compare the latency across the two cellular generations, we observe that the 5G latency is always lower than the LTE latency at the 5th, 50th, and 95th percentiles. We note that this result contradicts the result of a recent 14-month measurement study (07/22-09/23) across 8 cities in North America and Europe [22], which reports that 5G latency is often higher than LTE latency. This is likely due to a discrepancy in the methodology of latency measurements. The authors in [22] used ICMP ping to measure latency whereas the Speedtest app measures latency at the transport layer, by measuring the RTT of a pair of TCP PING-PONG messages after the initial handshake and warm-up phase of a TCP connection.

To confirm this explanation, we performed over 100 sets of RTT measurements in Boston while alternating between the two latency measurement methods every 10 measurements and plot the result in Fig. 4. Fig. 4 shows that, when the latency is measured using TCP packets, it is indeed much lower over 5G than over LTE (except for a few outliers); and when the latency is measured using ICMP packets, the gap between the median values over LTE and 5G is much smaller, and the 5G latency exhibits a much higher 75th percentile value than the LTE latency, which agrees with the result in [22]. Our results suggest that the popular approach of measuring round trip latency using ICMP packets may not yield reliable results over 5G networks (possibly due to operator policies assigning lower priority to ICMP traffic at 5G base stations) and should be replaced with a TCP-based approach.

5.4 Summary

In summary, our longitudinal analysis shows that:

(1) 5G Coverage can be divided into 4 phases: slow start, rapid growth, slower growth, and stable period. (2) 5G downlink throughput can also be categorized into 4 phases: initial excitement, increasing trend, stability, and finally another increasing trend. However, these four phases do not fully align with the four coverage phases.

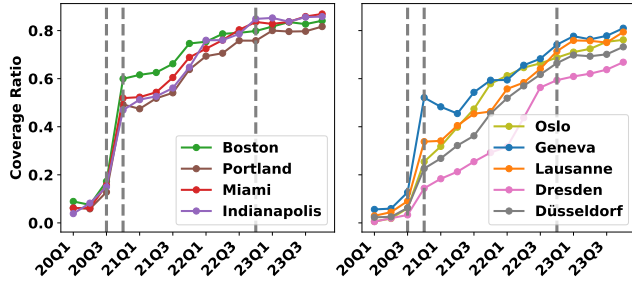


Figure 5: 5G coverage ratios per quarter for different cities.

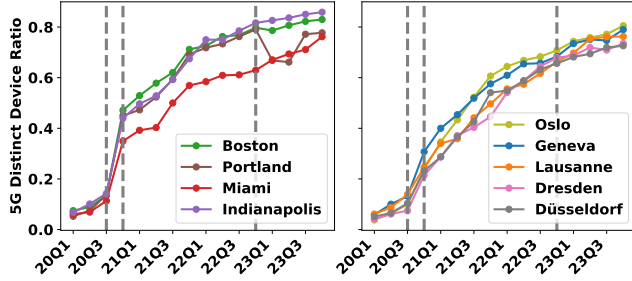


Figure 6: 5G device ratios per quarter for different cities.

(3) 5G latency exhibits a slightly decreasing trend in the most recent quarters and is overall lower than LTE latency.

6 Cross-Sectional Longitudinal Study

In this section, we study the evolution of 5G (coverage and performance) for individual cities in a cross-sectional longitudinal study, comparing their trends with the overall trends we identified in §5. We limit our focus to 5G, as we saw in §5 that LTE performance has remained mostly stable over the past four years.

6.1 Coverage

Figs. 5 and Fig. 6 plot the 5G coverage ratio and the 5G device ratio per quarter for each city. We examine these according to the trend phases we identified in Section 5.1 and make the following observations:

- (i) For phase **C1**, the overall trend (Fig. 2) holds for all cities. The US cities and Geneva have a slightly more pronounced increase in coverage ratio from 2020 Q2 to Q3 than the remaining EU cities.
- (ii) For the next phase, **C2**, the overall trend also holds for all cities, but again the rapid growth in 5G coverage ratio during **C2** is more pronounced for the US cities and Geneva compared to the other EU cities. The US cities and Geneva have a 32% to 42% increase in 5G coverage during **C2**, while the other EU cities have an 11% to 24% increase.
- (iii) In phase **C3**, all cities show an increasing trend in 5G coverage ratio, but growth in U.S. cities appears slower compared to EU cities. Notably, while Geneva experienced a sharp rise in coverage in the previous phase, its coverage ratio dropped for the first two quarters of **C3** before realigning with the overall upward trend. On the other hand, Dresden, which had the smallest increase during phase **C2** (only about 10%), exhibits a sharp increase during 2022 Q2 and Q3 by about 25%.

(iv) In the final phase, **C4**, the cities can be categorized into two groups: *Slower growth cities*: For US cities, the coverage ratio growth slows down significantly, with increases of only 1-5% from 2022 Q4 to 2023 Q4. *Consistent growth cities*: In contrast, the European cities continue to see steady growth, maintaining at least a 6-8% increase in phase **C4**.

Fig 7 and 8 depicts this evolution of 5G coverage ratio graphically for two cities, Boston and Dresden, having the fastest and slowest 5G coverage growth, respectively. They depict coverage at the end of each of the four phases. Each label is a distinct grid location, with the red (blue) labels representing 5G (LTE).

Overall, the results in this section suggest that *5G penetration in US cities evolved at a faster rate than in EU cities*. By the end of 2020 Q4 (phase **C2**), the 5G coverage ratio has reached 47-60% in the four US cities, while it ranges only between 15-34% in the EU cities (excluding Geneva). Similarly, the 5G coverage ratio reached 80% between 2022 Q3 and 2023 Q1 for the four US cities, while among the five EU cities, the ratio hit the 80% mark in 2023 Q4 for Geneva and Lausanne and it remained between 66-76% for the other three cities at the end of 2023 Q4. On the other hand, the growth has slowed down for the US cities in phase **C4**, while it continues at faster rates for EU cities.

The observed trends in the 5G coverage ratio in general follow the trend in the 5G device ratio, although with some striking exceptions. The sharp increase in the 5G coverage ratio for Geneva in 2020 Q4 to levels similar to those observed for US cities does not follow an increase of the 5G device ratio to similar levels, suggesting an aggressive 5G deployment by operators during phase **C2** in that city. A similar observation can be made for the sharp increase of the coverage ratio for Dresden in the first half of 2022. On the other hand, the coverage ratio dropped for Geneva at the beginning of phase **C3** although the device ratio continued to rise. Finally, in Portland, a surprising drop in the 5G device ratio by about 15% in 2022 Q4 did not affect the 5G coverage ratio.

6.2 Throughput

Fig. 9 and 10 show the 5G downlink and uplink throughput evolution for each city.

Downlink throughput. Examining the downlink throughput trends for individual cities in Fig. 9 in comparison to the phases identified in §5.2 (Fig. 3a), we make the following observations:

- (i) In the initial excitement phase, **T1**, different cities exhibit different patterns, consistent with the overall picture in Fig. 3a, which shows no clear trend for this phase. Boston, Indianapolis, and Miami are notable for their high 95th percentile values, which are typical of this phase due to the initial excitement about mmWave deployment, as noted in §5.2. Interestingly, Boston also exhibits a high 75th percentile (900+ Mbps) during all three quarters of phase **T1**, while Indianapolis and Miami exhibit a high 75th percentile only in the first quarter, suggesting that the initial excitement diminished faster in these two cities. In contrast, Portland's 95th percentiles are very low, suggesting a sparse mmWave deployment in the city. European cities, on the other hand, exhibit high median throughputs during phase **T1**, but very different trends. Oslo is the only city that exhibits a fast increasing trend during **T1**, suggesting a rapid 5G deployment, while Lausanne shows a fast decreasing trend. The

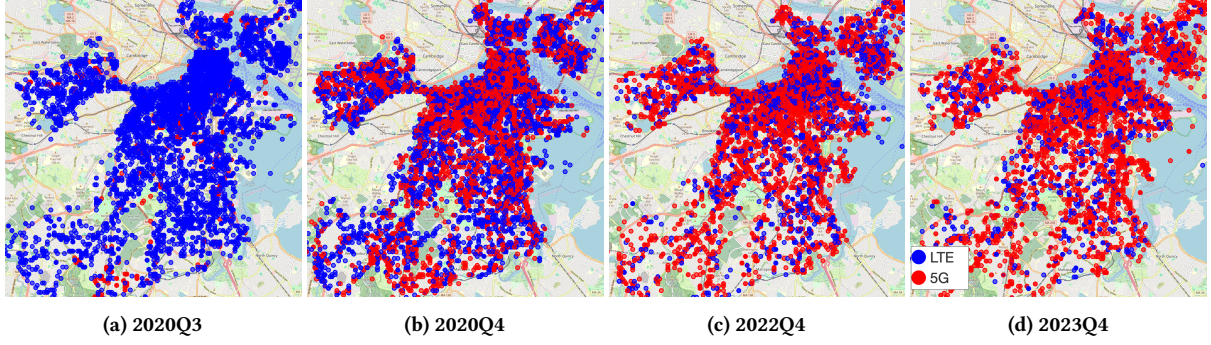


Figure 7: Boston coverage trend.

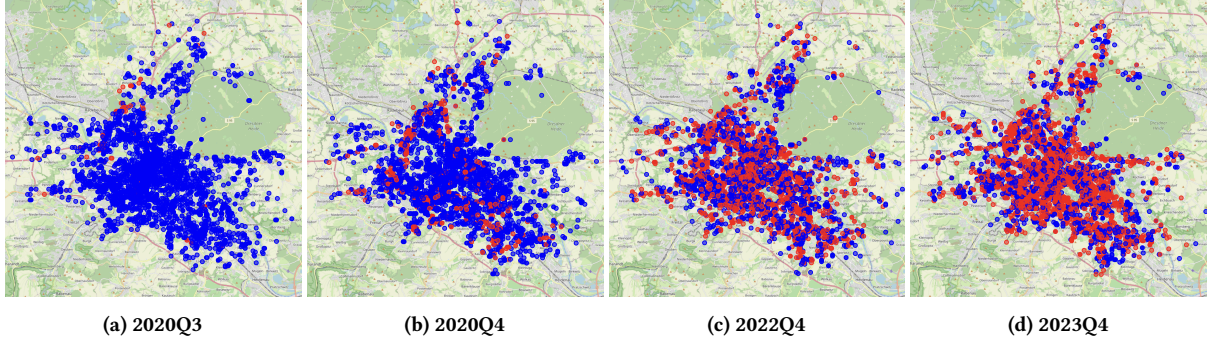


Figure 8: Dresden coverage trend.

other three EU cities exhibit no clear trend, consistent with the overall pattern in Fig. 3a.

(ii) In the next phase, **T2**, all U.S. cities and Geneva follow the overall trend of increasing median throughput. Dresden and Düsseldorf also show an upward trend in median throughput over the second half of phase **T2**, although the first two quarters deviate from this pattern. Lausanne exhibits a more stable median throughput during this phase, while Oslo displays an opposite trend, with a decreasing median throughput, after the fast increase during **T1**.

(iii) In the **T3** phase, the patterns observed in Boston, Indianapolis, Miami, and Düsseldorf align with the overall stable throughput trend for **T3** in Fig. 3a. Portland, on the other hand, shows an increasing trend, while Dresden initially experiences a decrease followed by an increase. In contrast, Geneva, Lausanne, and Oslo exhibit a declining trend during this phase.

(iv) In the final phase, **T4**, U.S. cities continue to follow an upward trend in throughput, consistent with the overall trend in Fig. 3a. In contrast, Dresden, Düsseldorf, Geneva, and Lausanne show the same median throughput in Q2 and Q4 of 2023, while Oslo's median throughput remains stable between Q3 and Q4 of 2023, lower than during 2023 Q2. This suggests that EU cities exhibit more stability in terms of performance in this period, unlike the continued increase observed in U.S. cities. It is likely that operators are still focusing on expanding 5G coverage (recall the fast increase of the coverage ratio compared to the US in Fig. 6) instead of rolling out new features that provide higher throughput. Nonetheless, it is worth noting that Oslo, in spite of the overall decreasing trend in phases **T3** and **T4**, still has a median throughput of ~ 350 Mbps in 2023 Q4, the highest among the 9 cities.

In summary, the evolution of the 5G downlink throughput in the four US cities aligns with the overall trends observed in Fig. 3a. This is justified if one takes into account the fact that the US cities contribute a larger number of data points in Fig. 3a (the total test count is slightly higher and the fraction of 5G tests is much higher in the 4 US cities than in the 5 EU cities, as shown in Table 1). In contrast, EU cities exhibit very different patterns (e.g., an increasing trend during **T1** or a decreasing trend during **T2** and **T3**), which do not always align with the overall trends in Fig. 3a. This can be explained in part by the fact that EU cities in different countries are served by different operators, which might follow different deployment strategies, although we also observe different patterns across cities in the same country (Dresden and Düsseldorf, Lausanne, and Geneva).

Uplink throughput. Examining the uplink throughput trends for individual cities in Fig. 10 in comparison to the phases identified in §5.2 (Fig. 3b), we observe the US cities have overall little variance across the quarters, in line with the overall trend. The only exceptions here are the first three quarters in Boston and Miami. In Boston, the uplink throughput exhibits an increasing trend in the first 3 quarters, before dropping to a lower value in 2020 Q4, while in Miami, the throughput is higher in the first 3 quarters compared to the remaining quarters. In contrast, the EU cities exhibit more variance in median throughput from quarter to quarter.

6.2.1 Impact of device 5G chipset and time of day. In the following, we attempt to explain the different throughput trends observed in Fig. 9 for different cities and understand why they do not always follow the overall trends observed in Fig. 3a. We focus on the downlink throughput, which is an order of magnitude higher

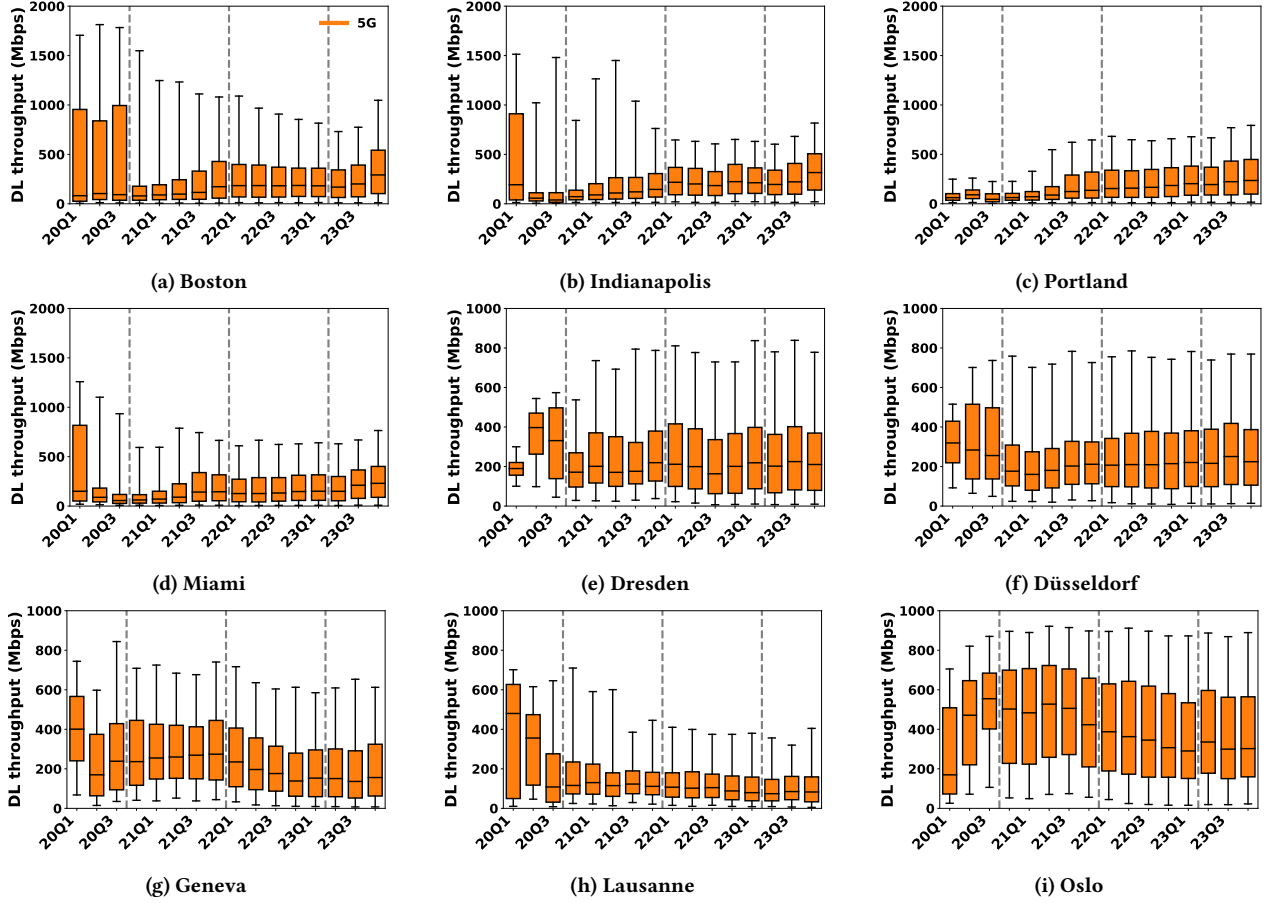


Figure 9: City-wise downlink throughput evolution (US cities have a different scale).

than the uplink throughput, making it easier to identify clear trends and phases. We explore two factors: the impact of the device’s 5G chipset and the impact of the time of day.

5G chipsets. We begin by looking at the device chipsets and their influence on performance trends between 2022 Q1 and 2023 Q4 (phases T3 and T4). Older chipsets (released before 2019 Q4) account for a smaller share of tests by 2023 Q4, as most users tend to upgrade their phones every 2-3 years on average [2]. Consequently, this analysis zooms into the last two years to explore how the latest generation chipsets correlate with network performance.

Fig. 11 highlights the top 10 chipsets based on median downlink throughput (release year in brackets) and their downlink throughputs presented in boxplots. A key observation is the significant performance gap between newer chipsets, like Chipset-1 (C1) and older ones, such as the Chipset-8, 9, 10 (median DL throughputs of 238 Mbps vs. 146 Mbps, 124 Mbps, and 88 Mbps, respectively). Additionally, the top 5 chipsets exhibit comparable peak performance (95th percentile) and are much higher than the bottom 5, with the exception of Chipset-8.

Fig. 12 presents the quarterly chipset distribution trends during phases T3 and T4 for four representative cities. Recall from Fig. 9 that Boston and Indianapolis exhibit a positive trend in downlink throughput during phase T4, while Oslo shows a decline during

both T3 and T4 and Dresden shows a decline only during the last quarter. We observe that Chipset-5, released in 2021, accounts for the largest share, contributing to 25-36% of tests. Meanwhile, the newly released Chipset-1 represents only 6.5-22%, suggesting its adoption is still growing. Interestingly, *chipset distribution patterns appear similar across these cities, suggesting that the shift in newer chipset usage does not directly correlate with throughput trends across these cities.*

Time of day. Another possible reason for the decreasing throughput trends in certain cities during phase T4 is congestion in the 5G network, i.e., the 5G infrastructure is improving slowly but the number of 5G users and their demands are growing at a higher rate. To analyze this effect, we divide the throughput into daytime (08:00 - 23:59 local time) and nighttime (00:00-07:59). If the nighttime throughput is higher than the daytime throughput, this is a sign of congestion happening in the daytime, as users are typically less active (i.e., generating less load) at night vs. during the day.

Fig. 13 shows the daytime and nighttime downlink throughput in the last year for 4 representative cities (2 US and 2 EU). The ratio of daytime to nighttime tests for each quarter comes out to be approximately 9 to 1 in all cities. Comparing the median throughput between day and night in Fig 13, we see that Boston and Indianapolis exhibit higher nighttime throughput, suggesting congestion

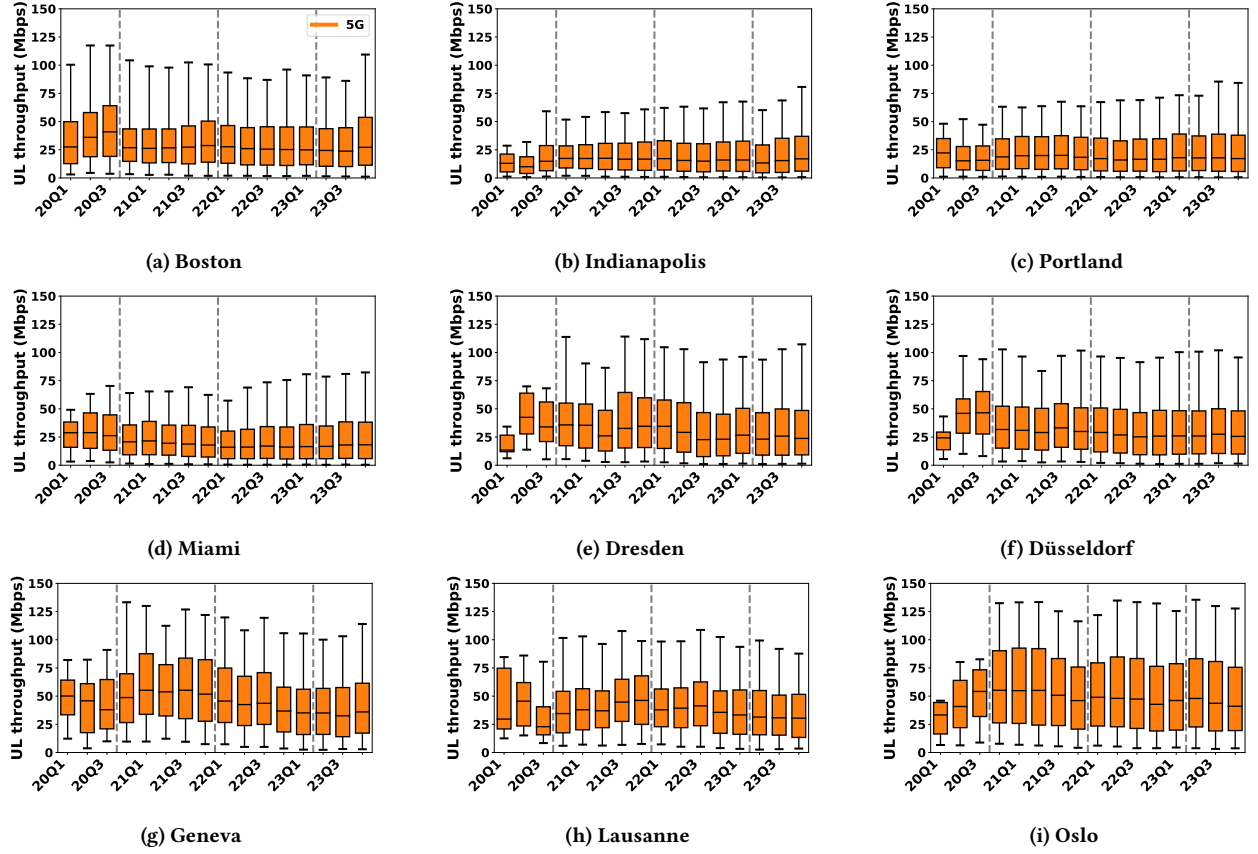


Figure 10: City-wise uplink throughput evolution.

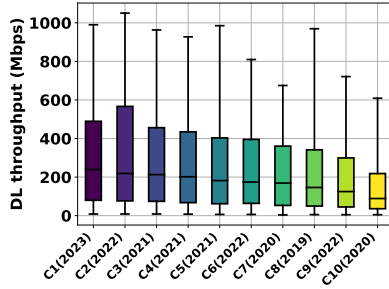


Figure 11: Downlink throughput distribution of different 5G chipsets.

during the day, but for the EU cities, the daytime throughput is almost the same as the night throughput, suggesting no congestion. Nonetheless, the two US cities exhibit an increasing throughput trend during 2023 in spite of congestion, while the two EU cities' throughput exhibits a decreasing trend or remains stable despite the lack of congestion. In summary, *there appears to be no correlation between changes in throughput (whether increasing or decreasing) in the final phase and the occurrence of congestion during this same period.*

6.3 Latency

Fig. 14 plots the city-wise 5G latency evolution over the 4-year period for the 9 cities. We observe a variety of patterns for different

cities, which diverge from the overall pattern in Fig. 3c. Specifically, we observe three patterns based on the median latency: (i) an increasing latency trend that stabilizes, (ii) a slowly decreasing latency trend, and (iii) alternating increasing and decreasing trends.

Boston, Geneva, Lausanne, and Oslo fall into the first category, with the latency of the Boston stabilizing to 25 ms and rest of the cities stabilizing to 18 ms in the last year. Indianapolis falls into the second category – in spite of a few oscillations, its median latency has an overall slow decreasing trend starting from 30 ms and ending at 20 ms. Portland, Miami, Dresden, and Düsseldorf fall into the third category, having both increasing and decreasing trends in the median latency over the 16 quarters. Portland and Miami have an increasing trend in the starting quarters and then a decreasing trend. Dresden has a high latency in the first 3 quarters (31-34 ms), which drops down to 25 ms in 2021 Q1, increases till 2022 Q3, and then remains stable. Finally, Düsseldorf has a high latency of 27 ms in the first 5 quarters, followed by a sharp decrease in the next 3 quarters, a stable period, and finally a slow increase in the last 3 quarters.

In summary, unlike the evolution of throughput, the evolution of latency in different cities does not align with the overall trends observed in Fig. 3c, as different cities exhibit very different trends. In fact, these trends can be different even between cities in the same country. Additionally, the 5th-to-95th percentile range in every

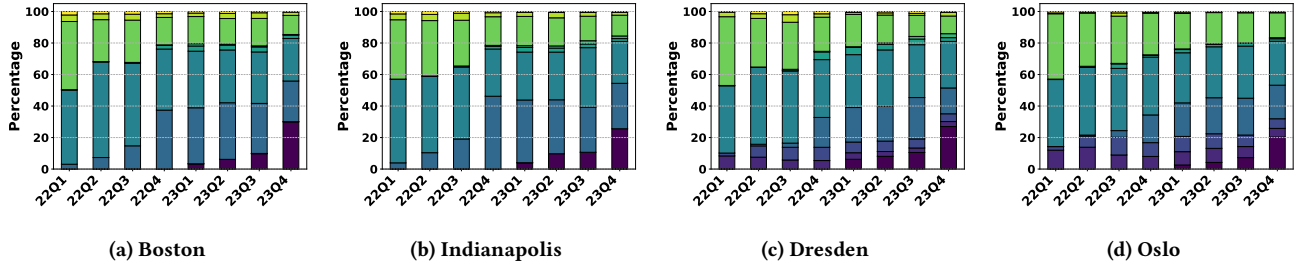


Figure 12: City-wise chipset distribution trend in 2022-2023.

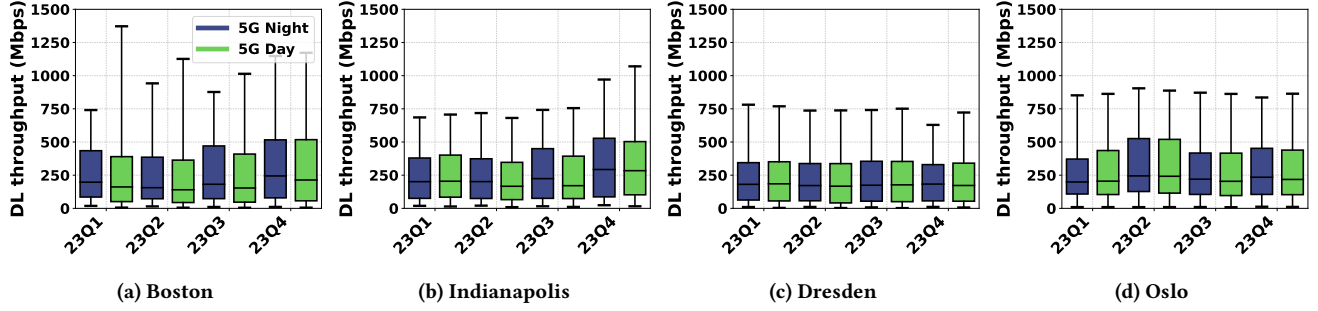


Figure 13: City-wise downlink throughput by time of day (2023).

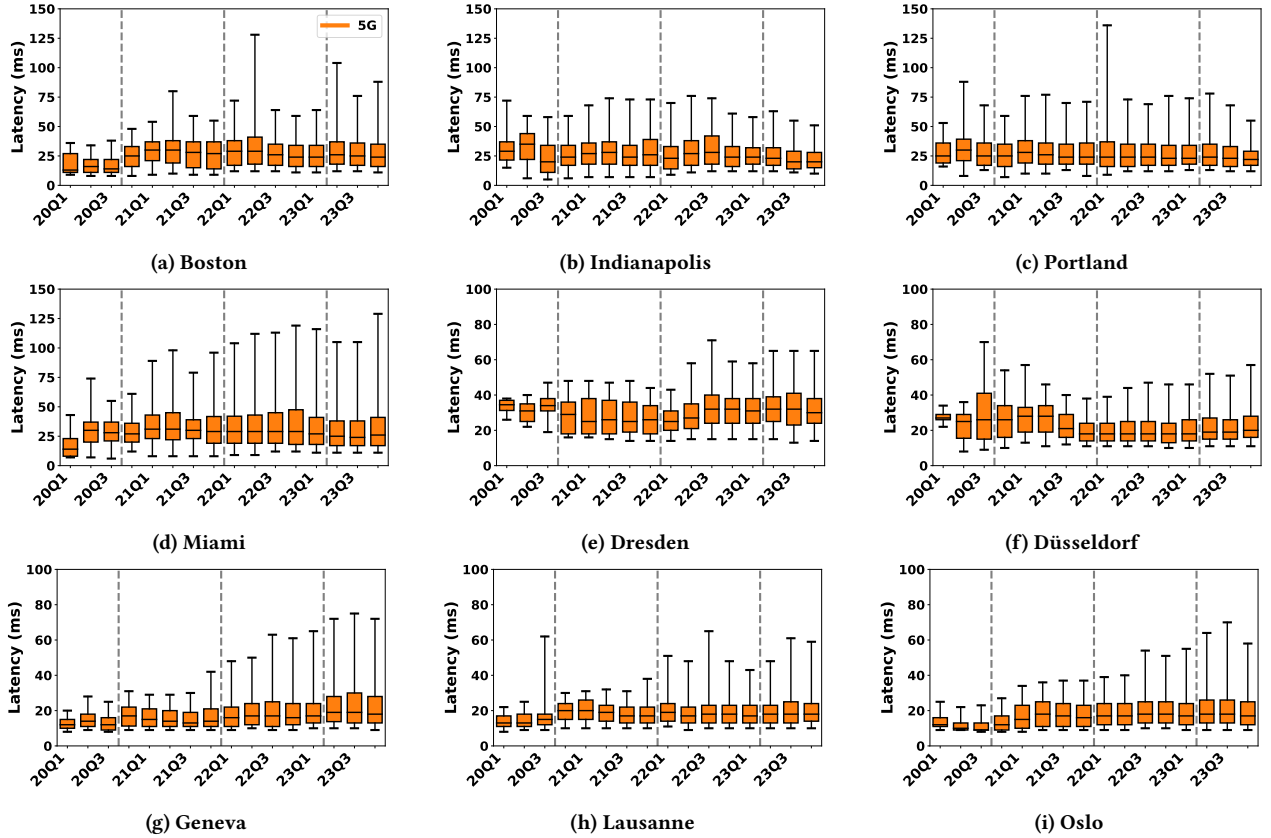


Figure 14: City-wise latency evolution.

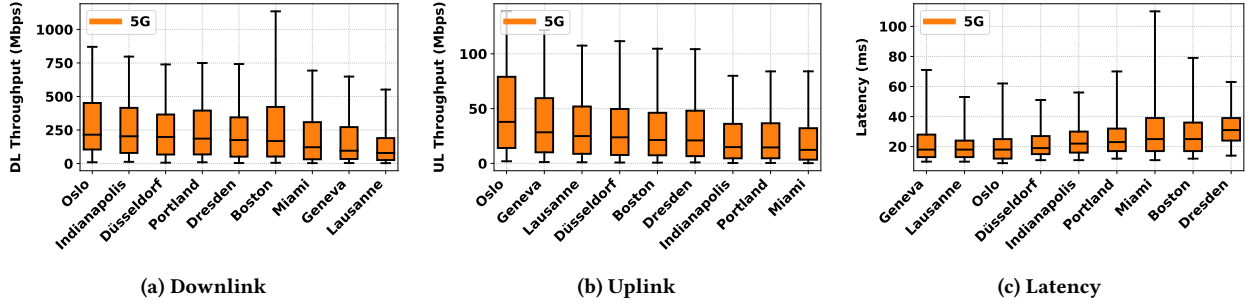


Figure 15: Cross-sectional: City-wise throughput & latency comparison (2023).

quarter is very high for certain cities, and it can vary drastically even for the same city between quarters.

6.4 Cross-sectional City-wise Study

In this section, we compare 5G performance across different cities in the US and EU. Fig. 15 plots the throughput and latency distribution of different cities in 2023. Note that, cities are sorted according to median downlink throughput.

Fig. 15a shows that Oslo has the highest overall 5G DL throughput with a median/75-th percentile of 215/451 Mbps. Indianapolis comes second with a median throughput slightly higher than Düsseldorf (203 vs 197 Mbps). The two Swiss cities, Geneva and Lausanne, have the lowest 5G DL throughput with medians of 95 and 78 Mbps, respectively. Note that, due to mmWave deployment in US, Boston (ranked 6th in terms of median throughput) has the highest 95-th percentile (1.1 Gbps) among all 9 cities. However, European cities with 5G-sub6 GHz deployment like Oslo, Dresden and Düsseldorf (870, 741, 738 Mbps) still have higher or comparable 95-th percentiles than the rest of the US cities, Indianapolis, Portland, and Miami (797, 749, 693 Mbps).

Fig. 15b shows that the order is drastically changed in terms of uplink throughput. EU cities show higher median throughputs compared to US cities and Oslo shows the highest median/95th percentile uplink throughput of 37/138 Mbps.

Finally, Fig. 15c shows that Oslo (the city with the highest median DL throughput), Geneva, and Lausanne (the cities with the lowest median DL throughput) have the lowest 5G median latency (18 ms). US cities in general have higher median latency than European cities with the exception of Dresden. Interestingly, the two German cities, Dresden and Düsseldorf, exhibit a large disparity in terms of median values (31 ms vs 19 ms).

6.5 Summary

In summary, our cross-sectional longitudinal analysis shows that (1) Coverage growth for all cities follows the overall coverage trend. EU cities show a slower growth than US cities during phase C2 (with the exception of Geneva) but a faster growth during C4. (2) The downlink/uplink throughput trends in US cities typically follow the overall pattern, while EU cities diverge from the overall pattern. In particular, EU cities show an increasing downlink throughput trend in the last phase (T4), while the EU cities show a stable or decreasing trend. (3) The device chipset distribution does not appear to have any correlation with throughput increasing/decreasing trends as it

remains similar across different cities. (4) Signs of congestion are present in phase T4 for US cities but the presence of congestion does not explain any increasing/decreasing trends. (5) Latency trends across cities fall into three categories: (i) an increasing trend that eventually stabilizes, (ii) a gradually decreasing trend, and (iii) a mixed trend, showing both increasing and decreasing periods over time.

7 Operator Longitudinal Study

In this section, we conduct an operator-wise longitudinal study. For each country, we pick the top 3 operators by test count (labeled as Op-1, Op-2, and Op-3) and study the evolution of their 5G coverage ratio and downlink throughput. To maintain statistical significance, we exclude any operator's data for a given quarter if it contains fewer than 50 samples.

7.1 Coverage

Operator 5G coverage ratio is the ratio of distinct 5G test locations for a single operator to the total number of distinct test locations for all operators. Since one location can be covered by multiple operators, the sum of the 5G coverage ratio of the three operators can exceed 1. Figs. 16 and 18 plot the evolution of the 5G coverage ratios for the top 3 operators in the U.S. and EU cities, respectively.

The first observation from these figures is that *not all operators start the rollout of their 5G services at the same time*. While most operators exhibit a non-zero 5G coverage ratio by the end of 2020 Q3 (phase C1), we observe some European operators with zero coverage ratio till 2020 Q3 (Op-2 in Düsseldorf), 2021 Q2 (Op-3 in Geneva), 2021 Q3 (Op-3 in Oslo and Lausanne), or even 2021 Q4 (Op-2 in Dresden). In some cases, these operators grow fast after their initial rollout and get a coverage ratio similar to that of the other two operators by the end of phase C4 (Dresden and Düsseldorf); in other cases, they lag behind even at the end of phase C4 (Oslo, Geneva, and Lausanne).

Comparing the evolution of 5G coverage ratio for the top 3 operators, we can divide the 9 cities into 3 categories:

i) All three operators converge to similar coverage ratios by the end of phase C3. Indianapolis, Dresden, and Düsseldorf belong to this category. In Indianapolis, the coverage ratio of Op-2 exhibits a sharp increase to 50% in 2022 Q2, but drops down in the following two quarters, while Op-3 has a lower coverage than the other two operators till the end of phase C3. Nonetheless, all three operators converge to similar coverage (about 30-35%) during

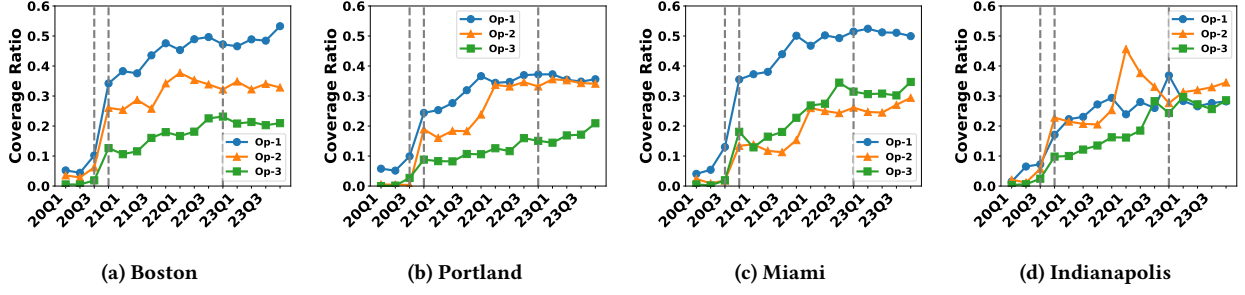


Figure 16: City-wise 5G coverage ratio for top 3 operators in US cities.

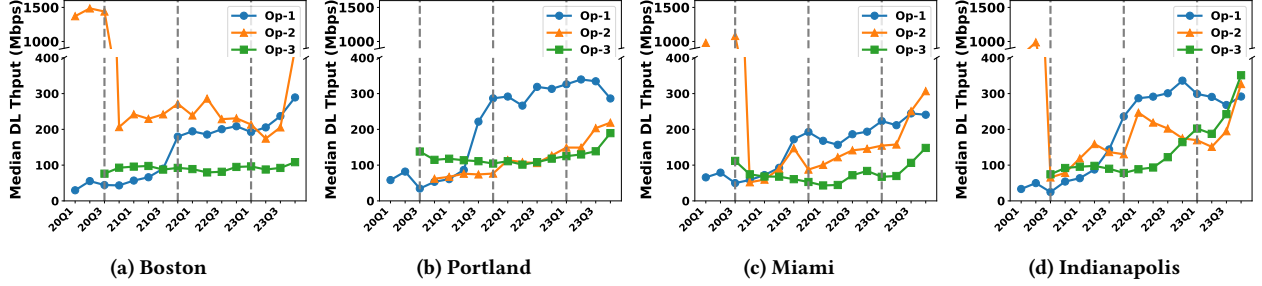


Figure 17: City-wise median DL throughput trend for top 3 operators in US cities.

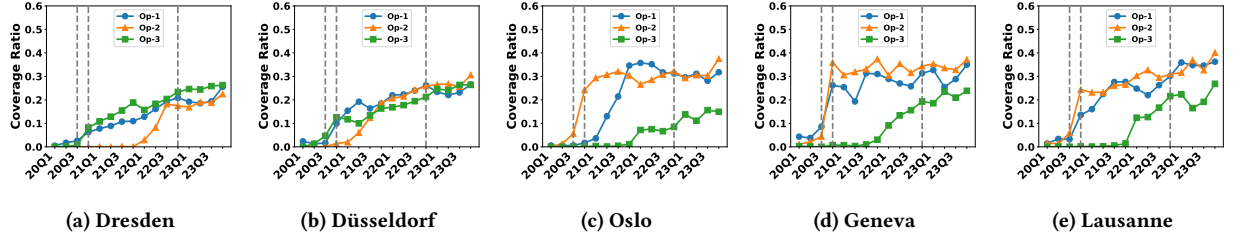


Figure 18: City-wise coverage ratio for top 3 operators in European cities

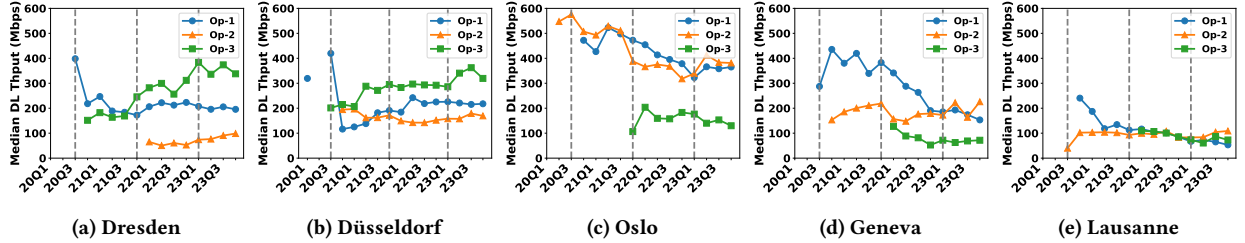


Figure 19: City-wise median DL throughput trend for top 3 operators in European cities.

phase C4. In Dresden and Dusseldorf, Op-2 rolls out its 5G services much later than the other two operators, but grows much faster and eventually achieves a similar coverage ratio as the other two operators by mid/end of phase C3, respectively.

(ii) **Two operators have (or converge to) similar coverage ratio, very different from the coverage ratio of the third operator.** Portland, Miami, Oslo, Geneva, and Lausanne fall in this category. In Portland, Oslo, Geneva, and Lausanne, two operators have similar coverage ratios, greater than the third operator (35% vs 20%, 30% vs 15%, 35% vs 20% and 35% vs 25%, respectively, at the end of phase C4), while, in Miami, two out of the three have similar

coverage ratios, lower than the ratio of the third operator (35% vs 20%, at the end of phase C4).

(iii) **The three operators have different coverage ratios through the 4-year period.** Boston is the only city in this category. The coverage ratio of the three operators increases at different rates during phase C2 and the gap between each pair of operators is maintained through the next two phases.

Additionally, we observe significant differences in the evolution of the coverage for the same operator in different cities of the same country. In the US, Op-1 reaches a coverage ratio of 50% or more, much higher than the ratio of the other two operators, in Boston and Miami, but has a much lower coverage ratio (30-35%), similar to the

ratio of at least one other operator in Portland and Indianapolis. In Germany, Op-3 rolled out its 5G services one year later in Dresden than in Dusseldorf. In Switzerland, Op-1 and Op-2 have a much faster growth during phase C2 in Geneva than in Lausanne.

7.2 Throughput

Next, we study the evolution of the median downlink throughput for the top 3 operators in the US and EU cities. Figs. 17 and 19 show that the operator with the most delayed rollout of 5G services typically has the lowest throughput over the entire 4-year period, with the exception of Lausanne, where the throughput of all three operators converges to a very low value at the end of phase T2. On the other hand, *the operator with the highest 5G coverage ratio among the three operators does not necessarily have the highest throughput*, suggesting that different operators adopt different deployment strategies, prioritizing one of the two metrics.

In the US, Op-1 has a much higher coverage ratio than the other two operators in Boston and Miami in phases C2, C3, and C4, however, its throughput is similar to or lower than Op-2's throughput in phases T2, T3, and T4. On the other hand, in Portland, Op-1 and Op-2 have similar coverage ratio from 2022 Q2 onward, but Op-1 has much higher throughput in the same interval. Similarly, in Indianapolis, Op-2 has a higher coverage ratio than Op-1 in the intervals from 2022 Q2 to 2022 Q4 and from 2023 Q2 to 2023 Q3, but its throughput is lower than Op-1's throughput in the same intervals.

Similar discrepancies are observed in Europe. In the two German cities, all three operators have similar coverage in phase C4, but Op-3 has much higher throughput in the same interval. In Geneva, Op-1 and Op-2 have similar coverage in phase C3, but Op-1 has much higher throughput in the same interval (spanning phases T2 and T3).

7.3 Summary

Our analysis shows that operators in the same city exhibit different patterns in the evolution of their 5G coverage ratios, and they do not start their 5G rollout at the same time. In particular, in European cities, some operators have 0% 5G coverage ratio until the end of 2021 or the beginning of 2022. Similarly, they exhibit very different throughput trends; in fact, operators with the highest 5G coverage ratio in a city do not always have the highest throughput. Our results in this section show how the dynamics and the competition among operators shapes a city's overall trend.

8 Conclusion

In this paper, we reported, to our knowledge, the first *metamorphosis* study of a cellular network generation – 5G. By analyzing a 4-year (Q1 2020 to Q4 2023) dataset of 2.65+ million Ookla Speedtest Intelligence measurements over cellular networks collected in 9 cities from the US and EU, we gained many insights into user-experienced performance of 5G deployment from birth (beginning deployment) to maturity (steady state) and across diverse geographic locations.

We believe these insights can enhance society's understanding of the timeline for coverage and performance improvements in new-generation cellular networks, help shape consumer expectations for the quality and performance of future deployments, and assist policymakers in crafting regulations and policies that promote the timely and effective rollout of future cellular technologies.

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Appendix

9 Ethics

The dataset used in this study was provided to the authors by Ookla, LLC via a "Speedtest Intelligence Public Interest Research License" agreement between Ookla, LLC and the authors' institutions. The dataset is fully anonymized and does not reveal IP addresses, safeguarding the identities of individual users. This work does not raise any ethical concerns.