A First Large-Scale Study of Operational 5G Standalone Networks

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As 5G technology has reached its midlife, mobile operators are increasingly rolling out 5G Standalone (SA), which is pivotal in unlocking the full potential of 5G networks. Prior research has mainly focused on 5G Non-Standalone (NSA) performance, while comprehensive evaluations of operational 5G SA deployments remain scarce. Through two cross-country US driving trips (3200+ km) in 2023 and 2024, we conduct, to the best of our knowledge, the first large-scale study of T-Mobile's 5G Standalone (SA) deployment in the US, analyzing its evolution while comparing it head-to-head with 5G NSA. Our study shows a shift in the operator's 5G deployment priorities from 2023 to 2024 in favor of 5G SA compared to 5G NSA, with 5G SA deployments extending across diverse geographical areas. Advanced features, such as higher carrier aggregation with diverse band combinations and new frequency bands with different duplexing capabilities, allow SA to achieve better performance compared to NSA, whose peak performance has plateaued, reflecting limited upgrades as the operator transitions to SA infrastructure. Additionally, we examine the handover duration and uplink power control in SA and NSA networks, offering deeper insights into the operational dynamics of the two modes.

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

Additional Key Words and Phrases: 5G, Measurement, Network Performance, Dataset

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1 Introduction

The latest generation of cellular networks, 5G, promises ultra-high bandwidth and low latency, enabling a new class of applications such as Augmented and Virtual Reality (AR/VR) [31, 32, 35–37], Connected Autonomous Vehicles (CAVs) [46, 51, 58], and the Metaverse. To accelerate the deployment of 5G, most operators initially adopted the Non-Standalone (NSA) architecture, which leverages the existing 4G LTE core for control plane signaling while introducing 5G New Radio

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(NR) as a data connectivity layer. NSA has facilitated the rapid rollout of 5G, delivering significant improvements in throughput over LTE [16, 21, 22, 26, 27, 40, 41, 53, 56]. However, NSA's reliance on LTE introduces additional signaling overhead and limits the full potential of 5G, particularly in achieving ultra-low latency and maximizing network efficiency.

In contrast, the Standalone (SA) architecture represents a fully independent 5G network, operating without reliance on the 4G core and enabling advanced features such as network slicing, enhanced security protocols, and lower latency [4, 6]. While SA deployments began in the US in as early as 2020, they gained significant traction only in late 2022 [7]. Despite this progress, SA adoption remains in its early stages compared to NSA, with T-Mobile being the only US network operator offering 5G SA service in 2024. Understanding how commercial SA networks compare to NSA networks in terms of coverage, performance, mobility management, and network characteristics is essential as operators transition towards a fully SA 5G future.

Since the 5G rollout in 2019, a large number of studies [16–22, 24, 26–28, 33, 39–43, 45, 48, 49, 53–57] have measured various aspects of 5G performance including coverage, throughput, latency, carrier aggregation (CA), resource allocation, handovers, beamforming, and application QoE. However, all these studies either focus exclusively on 5G NSA networks [16–19, 21, 22, 24, 26, 27, 33, 39–43, 45, 48, 49, 53, 54] or inspect 5G SA networks in extremely limited scope [20, 28, 55–57], and hence do not provide a complete picture of 5G SA coverage and performance today. In particular, a number of important questions remain unanswered: *(i) What is the current coverage of 5G SA deployments compared to the existing NSA deployments? (ii) How do SA deployments differ from NSA deployments in terms of throughput, latency, mobility management, and other network characteristics? (iii) How has SA performance evolved over time, and does it address the initial gaps identified during its early deployment?*

To answer these questions, we conduct the *first large-scale* measurement study of T-Mobile's[1] 5G SA and NSA deployments in the US via two large-scale driving measurement campaigns (Boston to Chicago, Chicago to Boston) conducted 18 months apart (May 2023 and November 2024). Our study spans multiple frequency bands, both in the low-band (n71) and mid-band (n25, n41), and different duplexing modes (FDD and TDD). Unlike prior studies, which focused on short-term or limited-scale measurements, our dataset includes over 3200 km of drive tests and in-field network measurements across urban, suburban, and highway environments. The collected dataset covers key aspects of 5G SA and NSA network behavior, including downlink (DL) and uplink (UL) performance, latency, CA, mobility management, and transmit power control. Our analysis provides a multi-faceted comparison of SA and NSA deployments, highlighting their evolution and trade-offs. The key findings of our work are summarized as follows:

- 5G SA emerges as the leading deployment mode in 2024 with a drastically improved coverage over the past 18 months, from 23.8% in May 2023 to 63.3% in Nov. 2024. Our results show an initial stronger focus on urban deployment; however, by Nov. 2024, SA coverage has expanded significantly even outside large urban centers. Overall, our results highlight the operator's strategic focus on driving a substantial transition from LTE-dependent NSA to fully standalone 5G networks.
- SA has maintained higher DL throughput in both years despite NSA's improvements in 2024 due to refinements in LTE-5G dual connectivity. Further, SA demonstrates significant UL throughput improvements from 2023 to 2024, driven by the focused CA efforts and the capabilities of new smartphone models. In contrast, NSA UL throughput remained largely unchanged from 2023 to 2024 and NSA's peak performance across both years and both traffic directions appears to have plateaued. 5G SA also provides comparable or better RTT performance in comparison to NSA in both years. Overall, these results highlight the growing maturity of SA networks to provide better

[1]T-Mobile is the only major US operator with non-negligible 5G SA coverage.

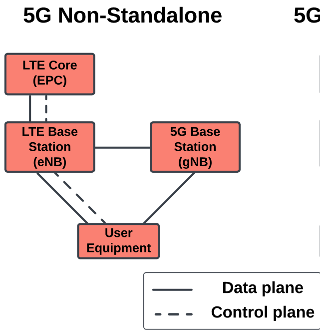


Fig. 1. 5G NSA vs. SA architecture.

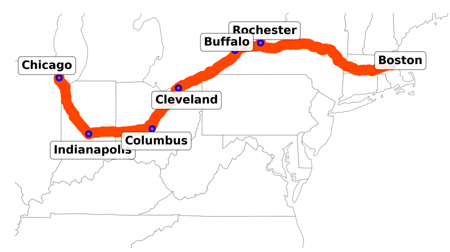


Fig. 2. Measurement Route.

performance, as well as the operator's focus on gradually phasing out NSA in favor of standalone 5G for long-term scalability.

• 5G SA supports higher CA levels than 5G NSA, resulting in a higher aggregate bandwidth and improved network performance. Additionally, the introduction of new frequency bands and duplexing modes in 5G SA, combined with the advanced capabilities of newer UE models, enables a large number of diverse CA configurations with intra-/inter-band CA and FDD/TDD combinations of up to 4 carriers in 2024 (vs. only 2 in 2023). The large diversity of available configurations offers the operator a variety of choices for its SA deployments that trade off performance, latency, and robustness, while reflecting the increasing complexity and maturity of SA deployments as 5G networks continue to evolve. In contrast, our results show that the operator has not advanced NSA's CA capabilities. The NSA mode aggregates at most 2 carriers in both years, in spite of the fact that newer UE models support higher aggregation levels.

• Surprisingly, we found that the 5G→5G handover duration is higher in 5G SA compared to 5G NSA due to rigorous signaling and advanced security mechanisms employed in the current 5G SA deployments. Nonetheless, the handover duration for both deployment modes and for intra-frequency SA handovers in particular has reduced significantly from 2023 to 2024.

• Our analysis shows that NSA uses higher control channel (PUCCH) transmit (Tx) power, largely attributed to NSA's deployments in non-urban areas, where greater pathloss necessitates higher Tx power to maintain effective communication with base stations. However, SA exhibits higher data channel (PUSCH) Tx power around 60% of time, even though it always achieves lower pathloss than NSA. Further breakdown of PUSCH power based on different traffic types reveals the operator's policies to elevate Tx power in the presence of UL-heavy traffic. This policy, combined with SA's high UL CA helps SA achieve superior UL performance in comparison to NSA.

Contributions. In summary, this work makes the following contributions: (1) We collect a large first-of-its-kind 5G SA and NSA dataset via two cross-country driving measurement campaigns, conducted 18 months apart, and spanning 3,200+ km. (2) Leveraging this dataset, we conduct the first large-scale, detailed characterization of T-Mobile's 5G SA network, examining coverage, network performance, mobility management, and other critical network features. (3) Our study offers a head-to-head comparison of 5G SA and NSA networks across two years, shedding light on the evolution and maturity of SA deployments. (4) Our dataset and scripts are publicly available [5].

2 5G SA and NSA architectures

Fig. 1 shows the fundamental architectural differences between the 5G NSA and SA modes. In 5G NSA, the 5G base station (gNB) is primarily responsible for data transmission, while the control plane operations are controlled by the 4G LTE core (EPC) via the LTE base station (eNB). The LTE base station can be used for data transmission in addition to the 5G base station in dual connectivity mode (EN-DC). In contrast, 5G SA operates independently, with its own 5G Core (5GC), allowing both control and data planes to function solely through the 5G infrastructure. This eliminates the dependency on LTE, enabling advanced 5G features such as reduced latency, enhanced security protocols, and network slicing.

3 Methodology

Measurement Route. We conducted two measurement campaigns, 18 months apart (May 2023 and November 2024), spanning over 3200 km of driving across the US. The route of the measurement campaigns is shown in Fig. 2. In May 2023 (05/13/2023 - 05/16/2023), we conducted a driving trip from Boston to Chicago, while in November 2024 (11/06/2024 - 11/08/2024), we drove from Chicago to Boston. We covered major cities along the route, including Rochester, Buffalo, Cleveland, Columbus, and Indianapolis. All measurement data reported in this study were collected on interstate highways, in suburban areas, and within city limits. Additional measurements were conducted within several major cities encountered along the routes. Our dataset includes more than 0.5 TB of data and 2580 minutes of measurements.

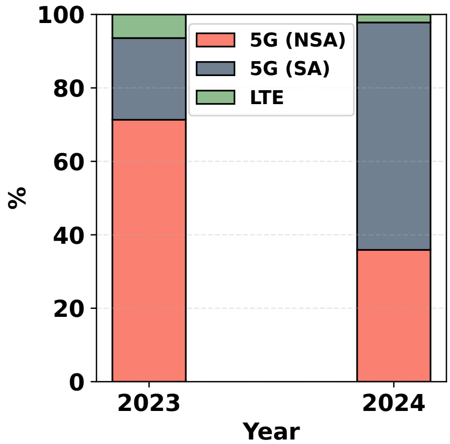
5G Carriers, User Equipment (UE), and Servers. We conducted measurements with all 3 major US operators – T-Mobile, Verizon, and AT&T. However AT&T provided no SA coverage while for Verizon the SA coverage was 0% and ≤ 1% in 2023 and 2024, respectively. Hence, we only consider T-Mobile in this paper. T-Mobile has a nationwide deployment of 5G low- and mid-band, and a very limited deployment of high-band (mmWave).

We used two smartphones – Samsung Galaxy S21 Ultra and Samsung Galaxy S24 Ultra – as our user equipment (UE) for data collection. In our 2023 drive, we used the Samsung Galaxy S21 Ultra model, which was still considered a state-of-the-art smartphone at the time of our measurements and was used in other 5G studies conducted around the same time (e.g., [21–23, 29]). In contrast, in our 2024 drive, we used the Samsung Galaxy S24 Ultra model, released in the U.S. in January 2024. Our goal was to capture the evolution of cellular performance for the two driven by both infrastructure and end-user device advancements. The S24 Ultra features a more advanced modem (Qualcomm Snapdragon X75 vs. Qualcomm Snapdragon X65 in the S21 Ultra). This upgrade enables the S24 Ultra to support higher CA in mid/low bands, with up to 4 component carriers (CCs) in the DL direction and up to 2 CCs in the UL direction, compared to the S21 Ultra's 2-CC/1-CC CA capabilities, and take full advantage of 5G SA's advanced CA features, as we show in §5.2. For our server-side infrastructure, we deployed an AWS EC2 server in Virginia.

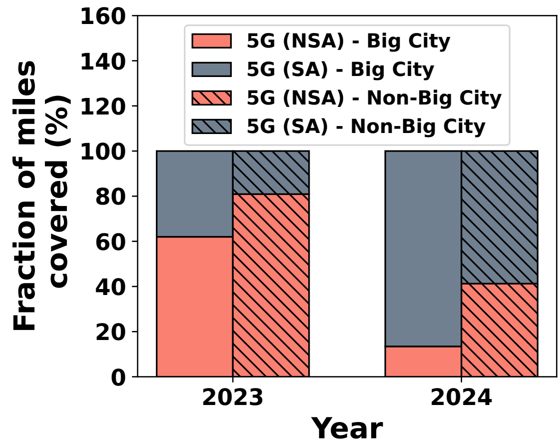
Experimental Methodology. We conducted backlogged DL/UL TCP throughput tests using nuttcp [44] and measured round-trip time (RTT) using ICMP ping in a round-robin sequence throughout each drive. Application-layer throughput and ping-RTT samples were logged at 500 ms and 200 ms intervals, respectively. Since commercial off-the-shelf smartphones do not grant access to low-level KPIs, such as 5G mode (SA vs. NSA), handover details, frequency bands, or CA, we employed Accuver XCAL Solo [13] devices to extract those features. These devices access the Qualcomm diagnostic interface of the smartphone, allowing us to capture signaling messages between the UE and the base station and to gather low-level KPIs essential for a comprehensive analysis of network coverage and performance.

4 Coverage

We begin by taking a closer look at T-Mobile's 5G SA and NSA coverage in the US. We define coverage for a particular technology as the fraction of miles driven under that technology over the total miles driven during our trips. Fig. 3a shows that in both years 5G (SA and NSA combined) was the prevalent technology during our driving route (93.6% of the total miles driven in 2023 and 97.8% in 2024). In 2023, 5G NSA was the leading 5G deployment mode with a coverage of 71.3%



(a) Overall SA vs. NSA coverage.



(b) Location-wise difference: SA vs. NSA.

Fig. 3. 5G Standalone and Non-Standalone coverage analysis.

of the total miles driven while SA coverage accounted only for 22.3%. In contrast, in 2024, 5G SA became the dominant deployment mode with a coverage of 61.9% vs. 35.9% for NSA. This significant shift reflects T-Mobile's focused and aggressive efforts to transition toward a fully standalone 5G infrastructure.

Next, we explore whether the SA and NSA deployment strategies vary based on location type. We categorize test locations as either "Big City" (within a 5-mile radius of the downtown of a city with a population over 300K) or "Non-Big City" (outside a 10-mile radius from the downtown of any big city)[2] and present the results in Fig. 3b. In big cities, SA coverage increased significantly from 35% in 2023 to 90% in 2024, highlighting the prioritization of SA deployments in urban, high user density regions, where there is a higher need for high-bandwidth and low-latency networks. Interestingly, even outside major urban centers, we observe non-negligible SA coverage both in 2023 and 2024: 19% and 58%, respectively. These results show a slower growth in SA coverage outside urban centers compared to the big cities, suggesting that T-Mobile first concentrated their efforts on SA deployments in urban areas before expanding into less populated regions. Nevertheless, we observe a clear decline in NSA coverage for both area types in 2024 indicating the operator's strategic move towards phasing out LTE-dependent 5G NSA networks in favor of a fully standalone 5G infrastructure.

We point out that during our driving tests, we had no control over the cellular technology to which the UE was connected. It is possible that a given location offers both NSA and SA coverage, and the operator's policies determine which of the two 5G technologies the UE will connect to at a given time. As such, the low NSA coverage in 2024 in Figs. 3a, 3b does not necessarily mean that T-Mobile has removed 5G NSA gNBs or replaced them with SA gNBs; it could also suggest that the operator heavily prioritized their SA service in areas where both modes were available.

To study this aspect in more detail, we conducted two smaller *controlled* driving experiments: one in Chicago, West Lafayette, IN, and the highway connecting the two cities, which was also part of our main drives in 2023 and 2024 (referred to as "Chicago"), and a second one in the city of Boston. In these experiments, we used two S24 phones side-by-side, and locked one of them to NSA

[2]Ideally, we would like to use the gNB location for our classification, but we only have the UE location, which can result in some misclassifications, when the UE is outside the 5-mile radius of a large city but is connected to a gNB inside the 5-mile radius. To avoid such misclassifications, we omit all the locations between a 5-mile and 10-mile radius.

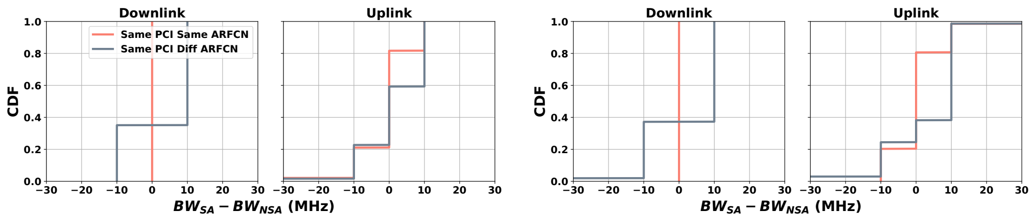
Table 1. T-Mobile NSA and SA head-to-head analysis.

(a) Coverage

	Chicago		Boston	
	LTE	**5G**	**LTE**	**5G**
NSA	5%	95%	8%	92%
SA	17%	83%	2%	98%

(b) Cell id (PCI) and channel number (ARFCN) Distribution

	Same PCI Same ARFCN	Same PCI Different ARFCN	Different PCI Same ARFCN	Different PCI Different ARFCN
Chicago	44%	40%	6%	10%
Boston	43%	38%	8%	11%



(a) Chicago. (b) Boston.

Fig. 4. Difference between NSA and SA PCell bandwidth in Chicago and Boston.

mode and the other one to SA mode using the operator service code *#2263#. When the locked mode was unavailable, the UE fell back to LTE. The coverage results are summarized in Table 1a.

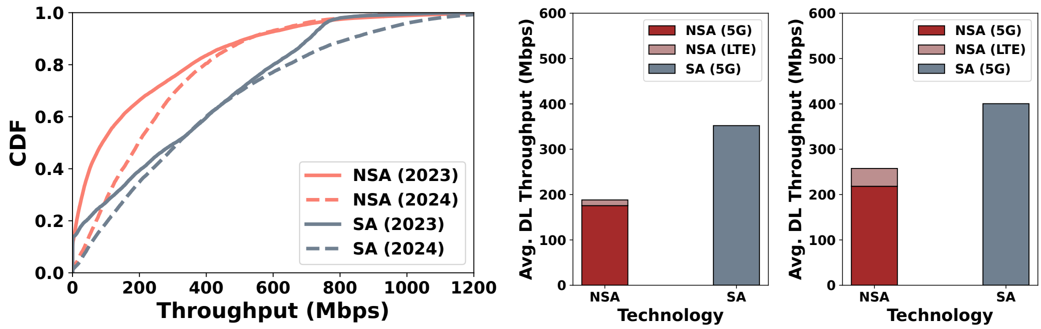
Table 1a shows very high coverage for both 5G deployment modes, confirming that T-Mobile often deploys both modes at a given location. In the Chicago drive, NSA coverage was 95% vs. 83% for SA. Interestingly, in the Boston drive, SA coverage is slightly higher than NSA coverage (98% vs. 92%), suggesting the existence of a small number of 5G gNBs offering only SA service.

Resource sharing between SA and NSA. For those locations where both 5G modes were available, we further look at the serving cell (Physical Cell ID/PCI) and the channel number (ARFCN) used by each mode in Table 1b. Table 1b shows that the prevalent deployment mode (84% in Chicago, 81% in Boston) in both datasets is to use the same serving cell for both modes. In contrast, cells offering only one mode appear less frequently – in 16% of the locations in Chicago and 19% of the locations in Boston.

For the locations where both phones connect to the same serving cell, the operator has two options to support both modes. It can either use the same channel for both modes and share the resources (e.g., via RAN slicing) or use a dedicated channel for each mode, offering performance isolation at the cost of higher spectrum usage. Interestingly, Table 1b shows a balance between the two options (44% vs. 40% in Chicago, 43% vs. 38% in Boston), with a slight preference towards the first option, which reduces spectrum usage at the cost of (potentially) reduced performance. In contrast, for the locations where each mode is served by a different cell, we observe a slight preference towards different channels for each mode (10% vs. 6% in Chicago, 11% vs. 8% in Boston) potentially to reduce inter-cell interference.

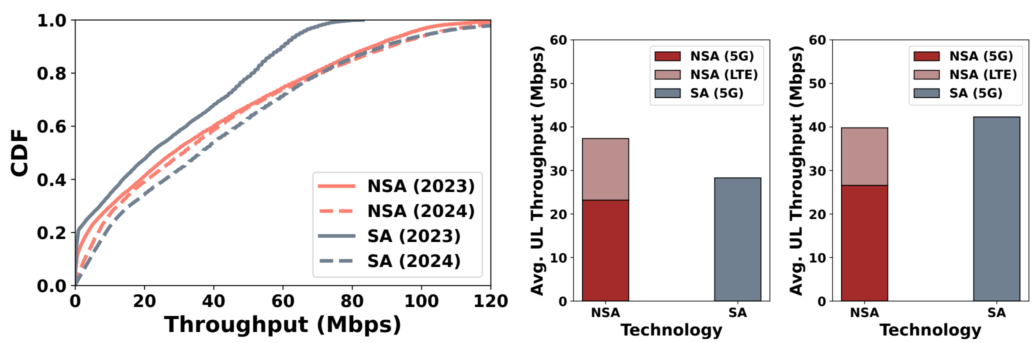
For the cases where both modes are served by the same primary cell, we further plot the difference in the primary cell's bandwidth used by each mode ($BW_{SA} - BW_{NSA}$) in Figs. 4a, 4b. When the same channel is used by both modes, the operator allocates the full channel bandwidth to both modes ($BW_{SA} - BW_{NSA} = 0$) in the DL direction (Figs. 4a(left), 4b(left)). In contrast, in the UL direction (Figs. 4a(right), 4b(right)), the operator allocates the full bandwidth to both modes 60% of the time, but splits the bandwidth *unequally* 40% of the time, favoring either of the two modes. When the two modes are served by different channels, SA is allocated a wider channel most of the time.

Overall, T-Mobile's 5G SA coverage has shown significant growth from 2023 to 2024, surpassing NSA as the leading 5G deployment mode. Although a higher prioritization of deployment is observed in large urban centers, the SA coverage has grown significantly even in smaller cities and rural areas. Our smaller focused studies suggest that the most common deployment mode is to upgrade NSA gNBs



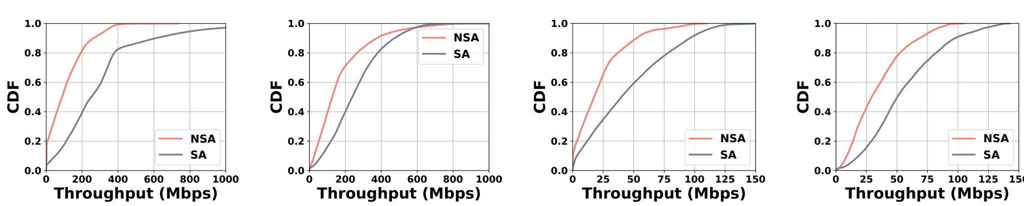
(a) Overall. (b) Breakdown (2023) (c) Breakdown (2024).

Fig. 5. NSA vs. SA: DL Throughput.



(a) Overall. (b) Breakdown (2023) (c) Breakdown (2024).

Fig. 6. NSA vs. SA: UL Throughput.



(a) Downlink (Chicago). (b) Downlink (Boston). (c) Uplink (Chicago). (d) Uplink (Boston).

Fig. 7. NSA and SA head to head performance comparison in Chicago and Boston.

to also offer SA services (using either the same or a different channel) instead of replacing NSA gNBs with SA gNBs or deploying additional SA cells.

5 Network Performance

In the previous section, our results showed high 5G SA coverage in 2024. In this section, we explore whether the high 5G SA coverage actually translates to better performance compared to 5G NSA.

5.1 Throughput

Fig. 5a shows the CDFs of DL throughput by 5G NSA and 5G SA in 2023 and 2024. For 5G SA, the median throughput remains the same in both years, but we observe an improvement in peak throughput (90th percentile) and worst-case throughput (20th percentile). For 5G NSA, there is a noticeable throughput improvement in 2024, especially in the lower and median percentiles, but the peak throughput remained unchanged. The improvement in 5G NSA throughput in 2024 is attributed to the refinements in LTE-5G dual connectivity (DC), as seen in Figs. 5b and 5c. Both the 5G and LTE (DC) average throughput have increased significantly to provide a combined overall higher throughput in 2024. Despite these improvements, 5G SA outperforms 5G NSA in terms of DL throughput in both years. Although the gap has narrowed in 2024 (from 218 Mbps to 119 Mbps in the median case), 5G SA still provides substantial gain over 5G NSA in terms of DL throughput.

Next, we analyze the UL performance of 5G SA and NSA. Fig. 6a shows the CDFs of 5G NSA and SA UL throughput for 2023 and 2024. We observe a completely different trend here compared to the DL performance. The UL performance of 5G NSA has remained largely unchanged from 2023 to 2024, whereas there is a significant improvement in UL performance of 5G SA over the same duration. The 25-th/50-th/75-th percentile of 5G SA UL throughput increased from 3/22/47 Mbps in 2023 to 12/36/64 Mbps in 2024. In fact, the 5G SA throughput was lower than the 5G NSA throughput in 2023, but higher in 2024.

Similar to DL throughput, we again break the 5G NSA UL throughput into 5G and LTE (DC) in Figs. 6b and 6c. We observe that in 2023, the throughput contribution from the 5G cell in NSA was actually lower than 5G SA throughput, but the LTE (DC) component helped 5G NSA achieve an overall higher throughput compared to 5G SA. In 2024, we observe a small increase in the contribution of the 5G component and a small reduction in the contribution of the LTE component, but the 5G SA UL throughput slightly surpasses the combined 5G and LTE NSA throughput. Again, this finding is contrasting to the DL performance (Figs. 5b and 5c), where we observed that both the 5G and LTE throughput for NSA increased from 2023 to 2024.

We note that the results in Figs. 5a, 6a are obtained by measurements at different locations, as the UE was connected only to one mode at a given location, and hence, they may be affected by various confounding factors (for example, the area type). For a more fair, head-to-head comparison, we again use our smaller datasets from the Chicago and Boston drives, collected with two UEs locked in NSA and SA mode, respectively. The results in Figs. 7a-7d confirm the results from our large-scale measurement campaign in 2024, showing a significant throughput gain in the median case for SA over NSA in both the DL (163/112 Mbps in Chicago/Boston vs. 119 Mbps in Fig. 5a) and UL direction (22/21 Mbps in Chicago/Boston vs. 5 Mbps in Fig. 6a).

Overall, we observe an increasing trend in 5G SA performance in both traffic directions, with SA consistently outperforming NSA in most scenarios. While NSA shows a noticeable improvement in DL performance from 2023 to 2024, its UL performance remained largely unchanged. Interestingly, the peak throughput values for NSA appear to have plateaued, indicating a possible shift in the operator's deployment priorities.

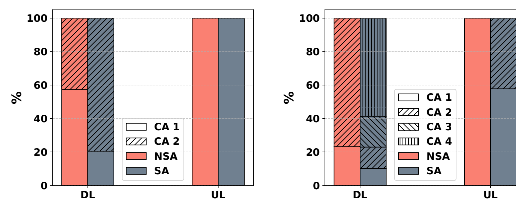
5.2 CA in 5G SA vs. NSA and its Impact on Performance

5G SA is expected to support higher CA [8–11], aggregating carriers from multiple frequency bands (mid and low bands) and different duplexing modes (FDD and TDD) in both traffic directions. High CA increases the aggregate bandwidth and has the potential to improve the overall network performance. In this section, we take a deeper look at the diversity of CA among 5G SA and NSA deployments, the different band combinations that exist, and the overall impact on network performance. Since CA is only performed under heavy traffic, we only use the data collected during download/upload tests for this comparison.

Overall CA Distribution. Fig. 8 shows the CA distribution for 5G NSA and 5G SA for 2023 and 2024 in both traffic directions.

In the DL direction, in 2023 both NSA and SA relied exclusively on 1-CC and 2-CC configurations, but the percentage of 2-CC configurations for SA is much higher than for NSA (80% vs. 42%). In 2024, 2-CC CA becomes the primary configuration for NSA (78%), while we observe the introduction of 3-CC and 4-CC configurations for SA (20% and 60%, respectively). We note here that these CA patterns are also influenced by the UE model. Recall that our measurements in 2023 were done with a S21 Ultra smartphone, which supported a maximum of 2 CCs. Hence, it is possible that the operator also allowed for CA of 3 and 4 CCs in 2023, but this is not reflected in our 2023 dataset due to the UE model. On the other hand, in 2024, even with the use of a better phone supporting higher CA, our results show that T-Mobile refrained from configuring higher CA for 5G NSA.

In the UL direction, we see lower levels of CA overall for both deployment modes in both years. In 2023, we observe no CA for either mode, which again could be due to the limitation of the S21 UE model, which did not support UL CA. In 2024, similar to the DL direction, even though the S24 model supports 2-CC aggregation, we observe 2-CC configurations only for SA (41% of the time), while 5G NSA still supports only 1 CC.



(a) 2023 (b) 2024

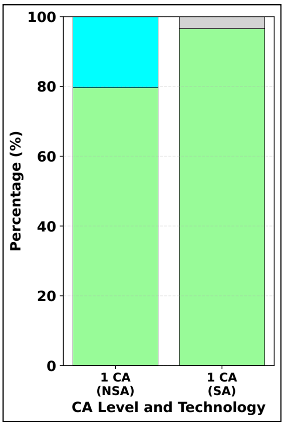
Fig. 8. CA distribution.

Band Combinations in CA. Fig. 9 shows the distribution of the different frequency bands aggregated for 5G NSA and SA in 2023 and 2024 in both traffic directions. Any band or band combination that appears less than 5% of the time is included in the "others" category.

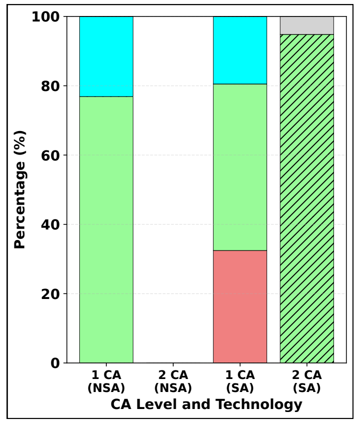
Figs. 9c and 9d show the band combinations for DL CA for 2023 and 2024. For NSA, the frequency band distribution has not changed drastically from 2023 to 2024. In 1-CC configurations, n41, which is the high-capacity TDD 5G-mid band, dominates as the primary band in both years, with a smaller percentage (25% in 2023, 29% in 2024) contributed by n71, which is a low frequency FDD band. With 2-CC aggregation, we again see a dominance of two n41 CCs aggregated in both years, and a small percentage (less than 6%) of 5G-low band (n71 FDD) and 5G-mid band (n41 TDD) aggregation in 2023, which slightly increases (11%) in 2024.

On the other hand, we observe several interesting trends in 5G SA. While in 2023 most of the 1-CC SA deployments were using the 5G-mid TDD n41 TDD band, in 2024, we observe around 46% of the time the use of 5G-low and 5G-mid FDD bands, including the newly available FDD 5G-mid band n25. For 2-CC configurations, in 2023, similar to NSA, we mainly observe the combination of two n41 CCs or n41 combined with n71 (with the difference that the primary cell here always uses the high-capacity n41 band). In contrast, in 2024, we observe a large diversity, with several combinations of n41, n71, and n25. Further, in 2024, for 3-CC and 4-CC configurations, we observe a significantly broader variety of band combinations, with a notable share of 'others,' indicating the presence of numerous less-common combinations that, while smaller in number, contribute to the overall diversity. These configurations show the growing complexity and maturity of SA deployments that leverage higher CA to maximize spectrum utilization and ultimately lead to better performance, as observed in §5.1.

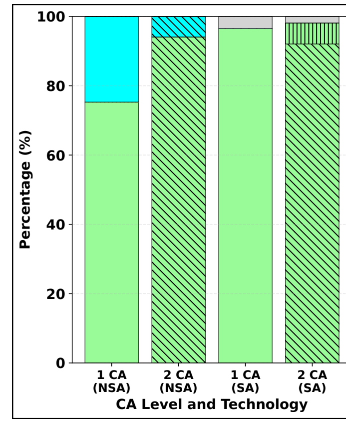
The availability of a large number of TDD and FDD combinations in 2024, particularly under 3-CC and 4-CC configurations, offers the operator a variety of choices for its SA deployments that trade off performance, latency, and robustness. The combination of a TDD band (n41, with a total bandwidth of 194 MHz) with an FDD band (n71 or n25, with a total bandwidth of 35 MHz and 65 MHz, respectively) can potentially reduce throughput compared to aggregating two wide n41 channels, but offers extended coverage and improved robustness [56]. As both FDD bands operate at lower frequencies – 600 MHz (n71) and 1.9 GHz (n25) vs. 2.5 GHz (n41), they have a higher range. As a result, the UE can continue using the lower-frequency FDD 5G band when it moves outside of the boundaries of the TDD cell, rather than downgrading to LTE. An additional benefit of the FDD bands is reduced latency, as DL and UL transmissions can take place simultaneously.



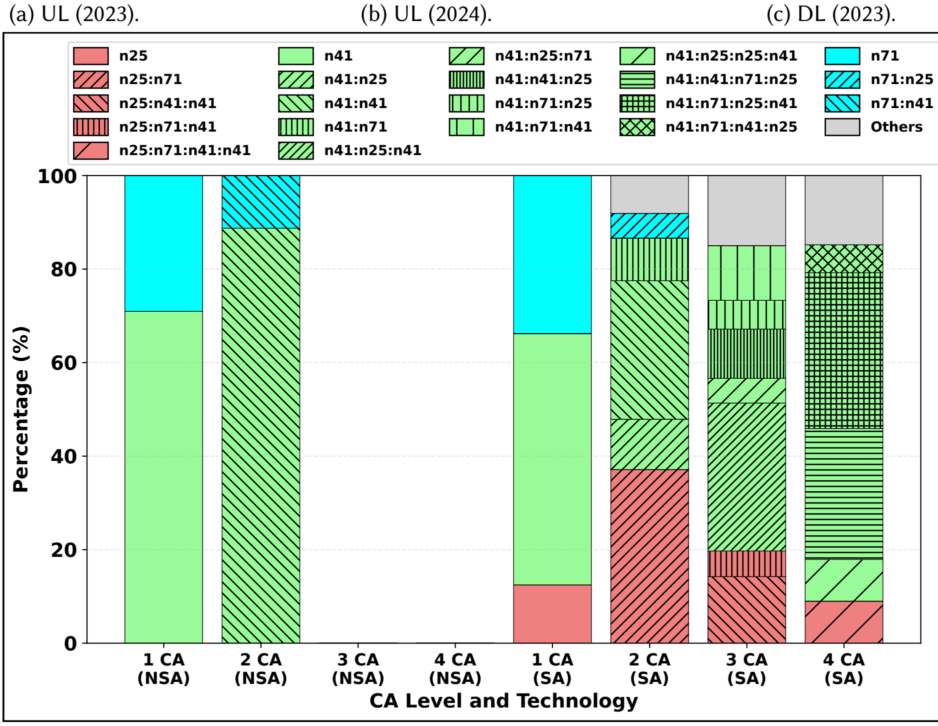
(a) UL (2023).



(b) UL (2024).



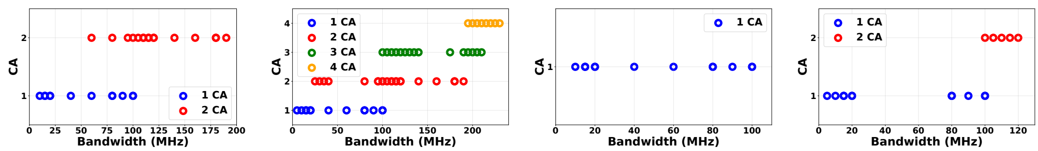
(c) DL (2023).



(d) DL (2024).

Fig. 9. 5G NSA vs. SA: CA and frequency bands distribution.

Next, we look at the distribution of frequency bands in the case of UL CA. Fig. 9a and 9b show the frequency band breakdown for different CAs in 2023 and 2024. Recall from Fig. 8 that NSA always uses 1 CC for UL communication. We observe similar band distributions for NSA in 2023 and 2024 with n41 being the dominant band and n71 used for a smaller fraction of time, similar to the DL direction. For SA, the trend for 1-CC configurations in the UL direction is also similar to the DL direction. The n41 band is used almost exclusively in 2023, while in 2024, low- and mid-band FDD n71 and n25 bands are often used, but n25 is given higher preference over n71, unlike in the DL direction. Interestingly, we observe almost no diversity in 2-CC configurations; the combination of TDD mid band n41 and FDD mid band n25, which balances performance and robustness, is used 95% of the time.



(a) NSA (DL). (b) SA (DL). (c) NSA (UL). (d) SA (UL).

Fig. 10. CA vs. aggregate bandwidth.

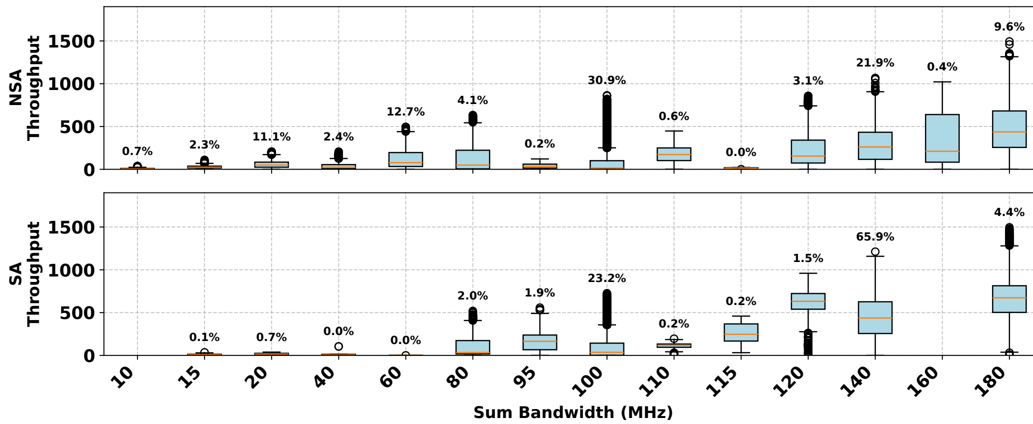
We note that, given the large number of available bands and channel bandwidth configurations (10-100 MHz), a higher CA does not necessarily lead to a higher aggregate bandwidth. This is clearly visible in Figs. 10a, 10b, which show the different CA and aggregate bandwidth combinations for NSA and SA, respectively, in the DL direction. In the case of NSA, we observe 2-CC configurations with aggregate bandwidths of 60, 80, and 90 MHz vs. 1-CC configurations over a wide channel of 100 MHz. Similarly, in the case of SA, we observe 2-CC configurations with lower aggregate bandwidth than 1-CC configurations, 3-CC configurations with lower aggregate bandwidth than 2-CC configurations, and 4-CC configurations with lower aggregate bandwidth than 3-CC configurations. In contrast, in the UL direction (Figs. 10c, 10d), 2-CC configurations always lead to higher bandwidth than 1-CC configurations.

Throughput and bandwidth correlation. In the previous section, we explored the diversity of band combinations in 5G SA and NSA and showed that a higher CA does not always lead to a higher aggregate bandwidth. In this section, we examine the distribution of the aggregate bandwidths resulting from using those diverse band combinations and investigate how the aggregate bandwidth correlates with throughput. Understanding this relationship will provide insights into the performance advantages enabled by wider bandwidths and more advanced CA configurations. Since the LTE component of the total NSA throughput is not related to the 5G bandwidth, we use the 5G MAC throughput in this section instead of the application layer throughput.

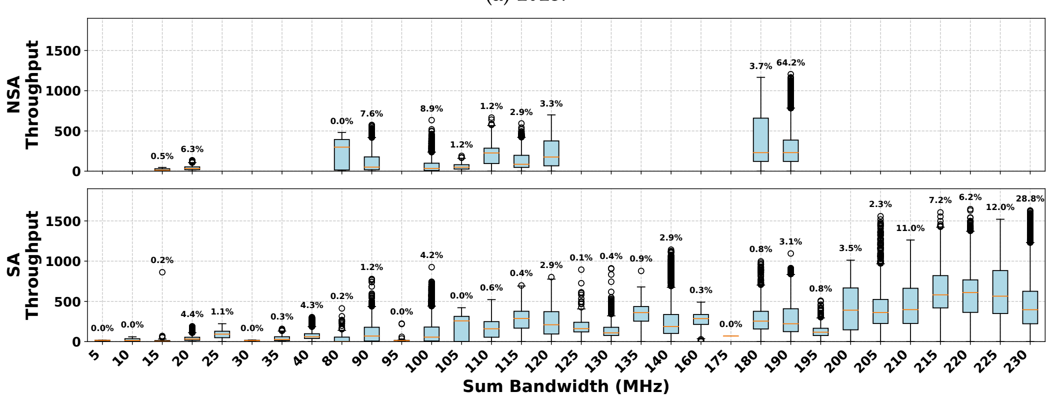
Figs. 11a, 11b plot the DL throughput vs. the aggregate bandwidth for NSA and SA in 2023 and 2024, respectively. The percentages above the boxplots show the fraction of samples of a given bandwidth in our dataset. The first observation we make from these figures is that the relationship between throughput and aggregate bandwidth is not strictly monotonic. The throughput of a cell is affected by many factors in addition to the cell bandwidth (e.g., MIMO, cell load, channel quality), which are outside our control. However, despite the lack of a strict monotonicity, we do observe that very low bandwidths (≤ 60 MHz) generally yield very low throughput and high bandwidths ($\geq$120 MHz in 2023, $\geq$200 MHz in 2024) generally yield the highest throughput.

In 2023 (Fig. 11a), NSA exhibits a more balanced distribution across low, medium, and high aggregate bandwidths, while SA demonstrates a strong tendency towards higher bandwidths, with a substantial number of samples (95.2% vs. 66.5% for NSA) achieving bandwidths of 100 MHz or more. Consequently, the higher bandwidth configurations in SA allow it to achieve better overall throughput compared to NSA, as shown previously in Fig. 5a.

In 2024 (Fig. 11b), we observe a large fraction (71%) of high-bandwidth configurations (200+ MHz) for SA, contributed by aggregating 3 and 4 CCs. On the other hand, since NSA aggregates a maximum of 2 CCs, the maximum aggregate bandwidth it achieves is limited to 190 MHz, which is the most commonly used aggregate bandwidth (64.2% of the samples vs. 0 samples in 2023). The large fraction of samples at 190 MHz bandwidth with a median throughput of 231 Mbps leads to a substantial improvement in NSA's overall throughput in 2024, as shown previously in Fig. 5a. On the other hand, the high-bandwidth configurations for SA do not improve its overall median throughput compared to 2023; in fact, the median throughput at the highest bandwidth of 230 MHz is much lower than the median throughput at lower bandwidths (215-225 MHz). However, they do lead to a substantial increase in its peak throughput, above the 90th percentile (Fig. 5a).



(a) 2023.



(b) 2024.

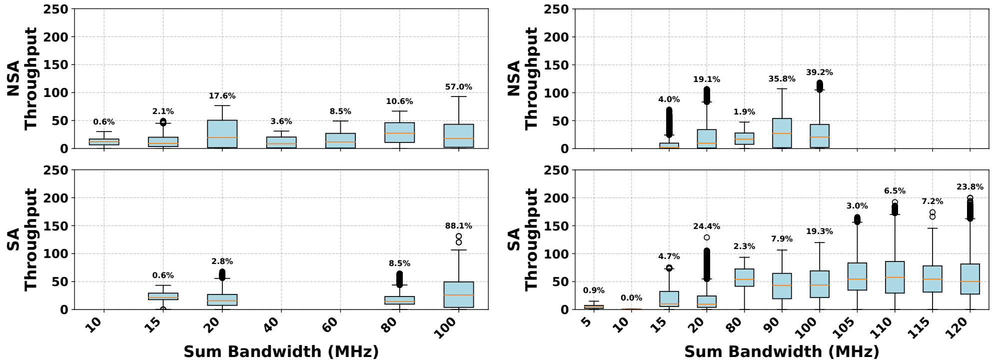
Fig. 11. NSA vs. SA: DL throughput vs. aggregate DL bandwidth in 2023 and 2024.

Next, we perform a similar analysis with UL bandwidth and throughput in Figs. 12a, 12b. Similar to the DL case, higher bandwdiths generally lead to higher throughput, although the throughput-bandwidth relationship again is not strictly monotonic.

Fig. 12a shows that in 2023, both deployment modes had a high percentage of 100 MHz aggregate bandwidth samples, which is the highest available bandwidth for a single CC (recall that in 2023 both SA and NSA used only 1-CC configurations in the UL direction). However, 5G NSA had a non-negligible distribution of low bandwidths (≤ 40 MHz) as well compared to SA, while SA used almost exclusively (96.6% of the samples) cells with 80 MHz or 100 MHz bandwidth, resulting in overall higher 5G throughput (Fig. 6b).

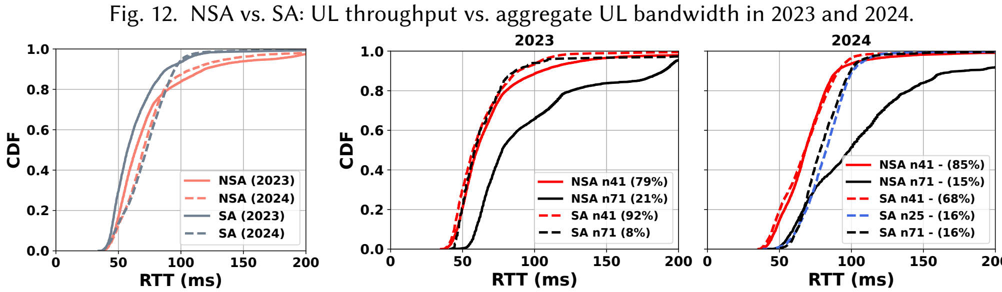
In 2024 (Fig. 12b), we see a very different picture for both NSA and SA. NSA now uses only 5 bandwidth configurations (vs. 7 in 2023). The fraction of 100 MHz samples has dropped significantly, from 57% to 39.2%, but we also observe a large fraction (35.8%) of 90 MHz samples (absent in 2023), which actually yield slightly higher throughput than the 100 MHz samples. In contrast, for SA, the introduction of 2-CC CA in 2024 leads to a large number of bandwidth configurations (9 vs. only 4 in 2023) from 5 MHz up to 120 MHz. The large percentage of samples above 100 MHz (40.5%) due to CA boost SA's throughput significantly in 2024 compared to 2023 (Fig. 6a).

In summary, our analysis shows the growing maturity of 5G SA deployments, leveraging higher CA and bandwidth configurations and diverse band combinations, which, combined with the advanced



(a) 2023. (b) 2024.

Fig. 12. NSA vs. SA: UL throughput vs. aggregate UL bandwidth in 2023 and 2024.



(a) Overall RTT. (b) RTT breakdown by frequency bands.

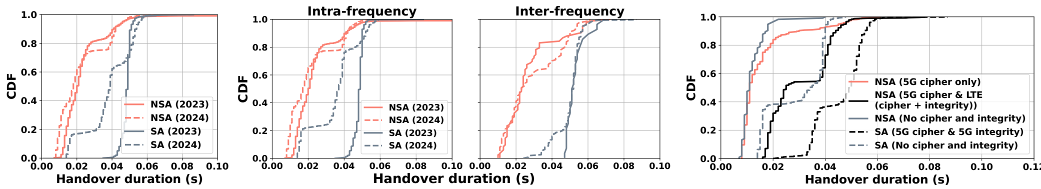
Fig. 13. SA vs. NSA RTT.

capabilities of newer UE modesl, enable SA to achieve higher performance compared to NSA. In contrast, the CA configurations for NSA remained largely static across both years (2-CC in the DL direction, 1-CC in the UL direction), even with more capable UE models, marking a clear plateauing of the peak achievable throughput. Overall, SA deployments show a clear trajectory towards higher bandwidth utilization and enhanced performance, underscoring their critical role in the ongoing evolution of 5G infrastructure.

5.3 RTT

Fig. 13a shows the CDF of RTT over NSA and SA in 2023 and 2024. In both years, the SA RTT is either similar to or shorter than the NSA RTT. This is expected, as in 5G SA, there is no reliance on the underlying LTE core for control plane interactions, which inflates the overall end-to-end latency for NSA. However, we observe that, regardless of the deployment mode, the RTT has increased in 2024 compared to 2023. The increase is higher for SA, while for NSA, the RTT actually has decreased slightly above the 80th percentile. We conjecture that with T-Mobile's aggressive deployment of 5G across the country, more users have been using 5G services, causing congestion and eventually inflating the RTT. A similar observation was reported in [25] for the years 2022 and 2024.

We further break down the RTT samples based on the 5G frequency bands in Fig. 13b. In 2023, the NSA RTT was much higher than the SA RTT in the n71 band, while the gap was much smaller in the n41 band. NSA's inflated RTT over the n71 band and the largest percentage of n71 samples in NSA compared to SA (21% vs. 8%) resulted in an inflation of the overall NSA RTT in Fig. 13a. In 2024, the RTT over the n71 and n41 bands increased substantially for both deployment modes. However, in the case of SA, we also see the appearance of the new n25 band, which operates in



(a) Overall. (b) Inter-/intra-frequency HO duration. (c) Impact of security keys exchanged.

Fig. 14. SA vs. NSA 5G→5G handover duration.

mid-band with FDD, and has the highest RTT among the three SA bands. The introduction of the n25 band and the much smaller percentage of n41 samples in SA in 2024 compared to 2023 (68% vs. 92%) contribute to the overall inflation of RTT for SA in 2024 and close the gap with NSA.

The high RTT for the n25 band appears counter-intuitive, as one would expect the RTT to be lower in an FDD system with dedicated DL/UL channels compared to a slot-based TDD system, where the latency should be higher because of asymmetric DL/UL slot distribution prevalent in today's cellular networks. Upon further inspection, we found that n25 uses a smaller subcarrier spacing (SCS) of 15 KHz compared to 30 KHz in the n41 band. The subcarrier spacing is the frequency gap between individual subcarriers in an OFDM signal. A larger SCS means that the frequency separation between adjacent subcarriers in the OFDM wave form is larger. This reduces the duration of each OFDM symbol and enables faster data transmission, which reduces the end-to-end RTT.

In general, SA consistently achieved either comparable or lower RTT than NSA, benefiting from the absence of the LTE anchor, which inflates the latency due to added control plane signaling. However, the inclusion of the new FDD band n25 in 5G SA in 2024 inflated the SA RTT and reduced the gap with NSA.

6 Handover Duration in 5G SA and NSA

Mobility management in cellular networks, especially the handover (HO) process, plays a key role in providing seamless and ubiquitous Internet access. NSA relies on the 4G LTE core for signaling and control-plane interactions while SA operates independently with its own 5G core. In this section, we focus on comparing the 5G→5G HO durations in the two deployment modes. [3]

Overall HO duration analysis. We define the HO duration as the time from the moment the UE receives an RRC Reconfiguration message from the network that instructs the UE to start the HO process until the moment the UE sends an RRC Reconfiguration Complete message to the network indicating a successful HO. Fig. 14a shows the 5G→5G HO duration for SA and NSA in both years. We make two observations. First, the HO duration for both technologies has decreased from 2023 to 2024. The drop is more pronounced in case of 5G SA, where the median HO duration decreased from 49 ms to 39 ms in 2024. Second, surprisingly, the NSA 5G→5G HO duration is always lower than the SA counterpart.

The second observation is counter-intuitive, as one would expect the NSA HO latency to be higher because of the involvement of an additional LTE cell over which the 5G cell is anchored to. However, we found that 5G→5G in T-Mobile's NSA deployment are done via a Secondary Node (SN) modification, which can be performed without the involvement of the LTE anchor [1, 14], thus significantly reducing the HO signaling. On the other hand, in the case of SA, the HO happens always between two 5G master nodes and involves a substantial amount of signaling between the two cells as well as the 5G core network. Higher signaling exchanges naturally leads to higher delay in the HO execution process.

[3]We also examined the HO failures for both modes. We found that the HO failure rate is very low – 1-2% for NSA and <1% for SA – in both years. Hence, we do not further analyze HO failure rate in this work.

Intra-frequency vs. inter-frequency HOs. We further break down the HOs into intra- and inter-frequency HOs in Fig. 14b. We observe that switching to a different frequency cell incurs higher latency for both NSA and SA in both years. This is expected, as a higher amount of signaling is required in the case of inter-frequency HOs, where the UEs need to adjust the radio carrier frequency for communication.

The reduction in HO duration for both intra- and inter-frequency HOs in 2024 compared to 2023 is lower for NSA than for SA. For SA, especially in intra-frequency HOs, we observe a drastic improvement in 25-th/50-th/75-th percentile HO duration from 2023 to 2024 highlighting the maturity and optimization of SA deployments. Additionally, the minimum inter-frequency HO duration for SA in 2024 decreased to 24 ms (from 47 ms in 2023) and around 25% of the samples are considerably lower in 2024 compared to 2023. However, across both HO types and years, the HO duration for NSA is still lower than for SA.

Impact of security key exchanges. 5G SA networks introduced enhanced security mechanisms [2, 4, 6] compared to existing 5G NSA and LTE networks by incorporating stricter security measures, particularly in the context of key exchanges. The key exchange process includes both ciphering and integrity protection that ensures confidentiality and authenticity of signaling messages and user data. These security mechanisms play a crucial role in determining the HO duration. We check the RRC Reconfiguration message sent by the network to initiate a HO for the type of security keys that are exchanged and break down the HO duration based on the type in Fig. 14c.

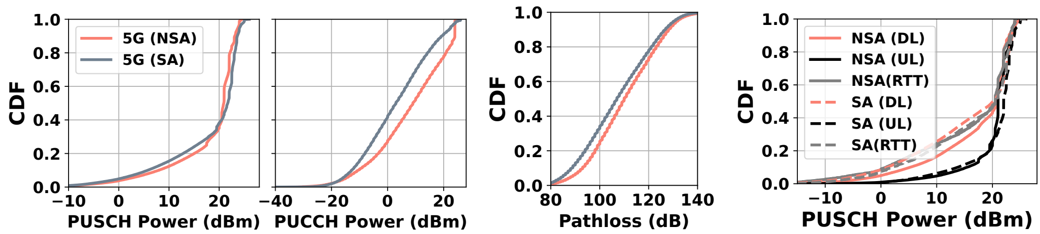
We observed 3 and 2 distinct scenarios w.r.t. key exchanges in NSA and SA, respectively. In NSA, the three scenarios are: (a) 5G cipher NEA2 (New Encryption Algorithm 2) used only for user plane data, as integrity protection for user plane data in dual connectivity is not supported [2], (b) 5G cipher NEA2 used for user plane data and LTE EEA2 (EPS Encryption Algorithm 2) cipher and LTE EIA2 (EPS Integrity Algorithm 2) integrity protection for signaling layers, and (c) No security keys exchanged. For SA, we have: (a) 5G cipher NEA2 and integrity protection NIA2 for both signaling and user plane data, and (b) No security keys exchanged.

In Fig. 14c, the HO duration for the cases where both the cipher and integrity protection keys are exchanged is the highest for both modes. In this scenario, the duration for NSA is comparatively shorter than for SA, probably because the 5G user plane does not have integrity protection due to dual connectivity in NSA. In contrast, in SA, both signaling and user plane data have ciphering and integrity protection key exchanged during the HO. Moreover, NSA relies on LTE's EEA2 and EIA2 for ciphering and integrity protection, whereas in SA, more advanced NEA2 and NIA2 keys are exchanged with stringent security measures leading to higher HO duration.

When only 5G cipher is exchanged without any LTE cipher or integrity protection (for NSA only), the HO duration reduces significantly. This is expected, as in this scenario, there is no active involvement of the LTE anchor, and the dearth of signaling between the 5G cell and the LTE anchor cell reduces the latency considerably.

Finally, we take a look at those cases where no security-related keys were exchanged in SA and NSA. For SA, the duration drops to a minimum duration of as low as 14 ms and most samples are less than 40 ms. This is a significant reduction w.r.t. to the case where both the keys are exchanged in SA. For NSA, the HO duration when no keys are exchanged, is mostly similar to the duration when only 5G cipher key is exchanged for user plane data, with the gap between the two cases becoming substantial only after the 80th percentile.

Overall, there are multiple factors that affect the HO duration in SA and NSA. NSA benefits from reduced signaling overhead in cases where the LTE anchor is not involved in the 5G⟶5G HO, which minimizes the HO delay. In contrast, SA introduces more signaling requirements and enhanced security mechanisms, such as exchange of NEA2 and NIA2 keys for signaling and user plane data. These rigorous checks ensure robust security but inherently increase latency. Additionally, the type of HO – intra-



(a) PUSCH and PUCCH power. (b) Pathloss. (c) PUSCH by traffic type.

Fig. 15. Overall PUSCH power and PUCCH power for SA and NSA; Pathloss in SA and NSA; PUSCH power breakdown by traffic type.

vs. inter-frequency – also impacts the HO duration. These findings underscore the trade-offs between reduced signaling complexity and latency in NSA versus robust security and independence of SA, highlighting the distinct priorities and challenges in mobility management for the two architectures.

7 Tx Power in SA and NSA

UL transmit (Tx) power is a critical metric in cellular networks, reflecting the strength of the signal used by the UE to communicate with the base station. UL Power Control (ULPC) in cellular networks [3, 12] is a mechanism used to adjust the Tx power of mobile devices in the UL direction. ULPC optimizes the quality and efficiency of the communication while minimizing interference to other users. It continuously adjusts the transmit power levels based on feedback from the base station, environmental conditions, and network requirements to maintain an optimal balance between signal quality and power consumption. In this section, we compare the PUSCH (Physical UL Shared Channel) power and PUCCH (Physical UL Control Channel) power for 5G NSA and SA deployments.

Fig. 15a shows the PUSCH power and PUCCH power for SA and NSA. We observe that the PUSCH power is comparable for the two deployment modes. The SA PUSCH power is slightly higher than the NSA PUSCH power 60% of the time but lower 40% of the time. On the other hand, the control channel PUCCH power for NSA is always higher compared to SA and the gap is much more pronounced compared to the PUSCH power. The median PUCCH power for NSA is 9 dBm, compared to only 3 dBm for SA.

To understand these differences, we plot the pathloss of NSA and SA in Fig. 15b. We observe that the pathloss for NSA is always higher than for SA, with the NSA median being 110 dB and the SA median being 107 dB. This explains why the PUCCH power for NSA is always higher than for SA. Since NSA has higher percentage of deployments in non-urban areas, i.e., highways, where the base stations are typically further away from the UEs, the UEs use higher PUCCH power to compensate for higher path loss due to longer UE-base station distance.

However, the higher pathloss for NSA does not explain why in Fig. 15a around 60% of the time the PUSCH power is lower for NSA than for SA. To explore further, we break down the PUSCH power based on the traffic type: backlogged DL traffic, backlogged UL traffic, ICMP-ping RTT tests in Fig. 15c. We observe that the PUSCH power is slightly higher for SA compared to NSA in the case of UL backlogged traffic, whereas for the other two types of traffic, where there is not much active UL traffic – TCP ACKs for DL tests and ICMP echo requests for ping tests – the SA PUSCH power is either similar to or lower than the NSA PUSCH power. This highlights the operator's policy to use higher Tx power for SA in presence of heavy UL traffic. This policy, combined with higher UL carrier aggregation for SA, explains the higher UL throughput observed in § 5.1 for 5G SA deployments compared to NSA.

8 Discussion

In this section, we discuss several unique aspects of our experimental mthdology and explain why they have only minimal influence on our findings.

(i) Head-to-head comparison between SA and NSA. Our primary objective in this work is to understand and compare coverage and performance of the two modes (SA vs. NSA) *from the perspective of a general user*. To this end, we conducted our driving campaigns with a single phone, without locking it to a specific network mode – thus reflecting how a real user would experience the network. We acknowledge that this methodology does not fully capture the actual coverage of the two modes: in many locations, both NSA and SA may be available, and the mode selected by the UE depends on the operator's policies. To mitigate this limitation, we conducted two smaller *controlled* driving experiments with two S24 phones in parallel, explicitly locking one to NSA and the other to SA. The details of these experiments have been described in §4 and the results in §4 and §5.1 align with the findings from our main driving campaigns.

(ii) Driving routes. Our two driving routes shared the same endpoints (Boston, Chicago) and followed the same highways, but the second trip was in the reverse direction. While this could in theory cause minor variations in UE–base station distance (depending on which side of the highway the vehicle was on), a difference of a few meters has negligible effect on received power and performance, especially for low- and mid-band frequencies.[4] Routes within downtown areas also varied somewhat due to traffic conditions, signals, or road closures. These differences are unlikely to affect our findings, as downtowns of large cities typically have dense 5G coverage.

(iv) Duration and time of measurement campaigns. The 2023 campaign lasted four days, with the final morning dedicated to downtown Chicago. In 2024, we covered downtown Chicago on the first day before departure. The overall duration is not critical, as both campaigns followed the same route. The campaigns were conducted in different months (May vs. November), which could influence traffic load but not coverage, and traffic is inherently outside our control. We deliberately scheduled the 2024 campaign in November to capture a more mature stage of SA deployment. Weather effects are negligible for low- and mid-band frequencies, and all measurements were conducted under clear skies.

(iii) Generalization of the results. Our results are based on measurements from a single operator, T-Mobile, the only US carrier with SA deployed at scale during our study. At the same time, major European operators had only NSA deployments [22]. The study focuses on the East Coast and Midwest along one driving route; we acknowledge that results may differ in other regions such as rural areas. Nonetheless, we point out that this is the largest measurement study of SA networks to date, with the exception of the work in [57], which focuses exclusively on the impact of NSA/SA on video streaming in China. As global SA rollouts accelerate, we expect our work to serve as a foundation for broader studies in other regions.

9 Related Work

5G Measurement Studies. Since the 5G rollout in 2019, a large number of studies [16–19, 21, 22, 24–28, 33, 39–43, 45, 48, 49, 53–56] have measured various aspects of operational 5G networks, including coverage, network performance, carrier aggregation, resource allocation, handovers, beamforming, and application QoE. Most of these studies are performed over commercial 5G NSA deployments. In contrast, 5G SA has received limited attention in the literature, particularly in terms of its large-scale evolution and comparative analysis with NSA.

Outside the US, only Yuan et al. in [57] study the performance of live video streaming over 5G SA and NSA networks in China from a content provider's perspective. They report that SA

[4] Recall that T-Mobile does not use mmWave bands, which have much shorter range.

results in lower broadcast and viewer buffer delays and rebuffer proportions than NSA. In the US, Narayanan et. al in [43] and Hassan et. al in [28] conducted preliminary measurements with T-Mobile's SA deployments before 2022, when T-Mobile deployed 5G SA operating only at 600 MHz (5G low band) in a fragmented and limited capacity in the US. T-Mobile started deploying 5G mid band SA services as their primary deployments in late 2022. The works in [20, 55] are the only ones that performed measurement-based analysis of SA networks after 2022. However, [55] takes a snapshot of the SA performance in only two cities with just 10 hours of measurements in April 2023, when SA networks in the midband just started getting rolled out. As a result, it does not include any measurements over the n25 band or with 4-CC CA. It also reports a maximum aggregate bandwidth of only 160 MHz for SA with 3-CC CA, while our study (§5.2) reveals a much larger diversity of aggregate bandwidths – up to 180 MHz for both modes in 2023 and up to 190/230 MHz for NSA/SA in 2024. On the other hand, [20] only evaluates the latency of control plane procedures (attachment and registration, RRC connection, authentication and security, PDN/PDU connection) at three locations without studying data plane performance or coverage, and hence, it is complementary to our study. To our best knowledge, there is no other large-scale measurement work studying the coverage, performance, and network characteristics of operational SA networks and comparing them head to head with the existing NSA network across different regions of the US over an extended time period.

5G SA Evaluation over Simulations and Controlled Environments. There have been several studies [15, 30, 34, 38, 47, 50, 52] on different aspects of 5G SA based on theoretical analysis, simulations, and measurements done in controlled settings. While these works offer valuable insights, they often fail to capture the full range of real-world scenarios, as different network operators implement unique policies and configurations that are difficult to replicate in controlled environments. Our work captures the real world performance of operational 5G SA networks via a large-scale measurement campaign comprising multiple cross-country trips.

10 Conclusion

We conducted the first large-scale measurement study characterizing the evolution of 5G Standalone deployments while performing a head-to-head comparison with the prevalent 5G Non-Standalone networks. Through two cross-country driving trips in the US (3,200+ km) 18 months apart, our work captures the comprehensive landscape of 5G deployment, performance, mobility management, and other network characteristics. Our study shows a significant improvement in 5G SA coverage from 2023 to 2024 with deployments in both urban and non-urban areas. In terms of performance, 5G SA demonstrates clear advantages in terms of both throughput and latency thanks to features such as high carrier aggregation and the use of newer frequency bands, which enable diverse intra-/inter-band and FDD/TDD configurations. In contrast, NSA peak performance has plateaued, primarily due to limited use of CA in NSA deployments. Furthermore, our analysis reveals some interesting information with regard to mobility management in SA and NSA networks, where the interplay between signaling complexity and security mechanisms plays an important role in governing the handover duration in 5G networks.

Overall, our study underscores the importance of continued investment in 5G SA networks to fully achieve the potential of 5G and by open-sourcing our dataset, we aim to support researchers in exploring 5G deployments towards more efficient and robust next-generation networks.

Acknowledgments

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Appendix

A Ethics

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