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A Closer Look at Stand-Alone 5G Deployments from the UE Perspective

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***Abstract*—5G Stand-Alone (SA) deployment is crucial for unlocking the full potential of 5G, providing significant improvements to mobile user experience and enabling the development of new applications. As mobile operators start rolling out SA-5G to the market, there remains a lack of comprehensive measurement studies, leaving many questions about its capabilities. To this end, we conducted a timely in-field measurement study in April 2023, covering two major US cities where T-Mobile has designated SA-5G as the dominant and default radio access technology. Our study gathered over 10 hours of insightful network traces under different mobility scenarios. Using these datasets, this paper examines the characteristics of the recent 5G SA deployment, data plane performance, and mobility management. Our study provides a revealing snapshot of the current state of SA-5G in the US. We show that SA-5G exhibits improved performance over NSA-5G in many areas. Whereas we also identify areas where SA-5G yields poorer performance over NSA-5G.**

***Index Terms*—Network Measurement, Stand-Alone 5G, Non-Stand-Alone 5G, Radio Access Network, End-to-End Performance**

I. Introduction

The fifth generation of wireless technology (5G) promises to provide enhanced mobile broadband (eMBB), ultra-reliable low-latency communications (URLLC), and massive machine-type communications (mMTC) services. These abilities enable a plethora of new applications, such as AR/VR [1], teleoperated vehicles [2], [3], and remote surgery [4]. However, due to concerns about deployment speed, cost, and technological complexity, many mobile operators have opted to deploy 5G in a Non-Stand-Alone (NSA) mode as a transition, utilizing the existing 4G infrastructure to support the network (see Section II for details). NSA-5G is capable of offering various 5G NR (New Radio) features such as flexible numerology, diverse radio bands (including mmWave radio), massive MIMO, among others. It has demonstrated remarkable improvements from the mobile user perspective [5], particularly in terms of throughput, as revealed by a flurry of measurement studies since the early stages of 5G deployment [6]–[12]. Nonetheless, due to its reliance on the existing 4G LTE as its "anchor" for control plane signaling (and dual-connectivity), the NSA-5G architecture introduces additional overheads, and may not fully realize the potential of 5G.

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TABLE I: Collected SA-5G Dataset Statistics.

Mobile operators	T-mobile	
Radio access technologies	NSA-5G, SA-5G	
Detected band	Low-band (n71), Mid-band (n25, n41)	
Measurement Venues	Minneapolis	Chicago
# of stationary locations	14 sites	9 sites
Cumulative walking distance	10km	N/A
Cumulative driving distance	105km	N/A
Cumulative data traces	∼650 min	

The Stand-Alone 5G (SA-5G) architecture represents a true 5G network. Several mobile operators have started rolling out the SA-5G deployment for some time, but often in a secondary and limited capacity. This has been the case as of November 2022, when T-Mobile designated SA-5G as its primary radio access technology and architecture in the US.

In this paper, we take the T-Mobile SA-5G deployment as a case study and conduct a thorough measurement study to address the following major questions: *What are the key characteristics of the commercial SA-5G deployment? How do they compare to NSA-5G?* and *What is the user experience of the current commercial SA-5G deployment?* To this end, we carried out thorough and timely in-field measurement experiments in two major cities in the US – Minneapolis and Chicago – during the month of April 2023. Our measurements collected over 10 hours of network and data traces from T-Mobile, the only mobile operator in the US with widespread deployment of SA-5G technology, utilizing both 5G low-band (n71) and mid-band (n25 and n41) frequencies. These measurements were conducted both indoor and outdoor, under different mobility scenarios, including stationary, walking, and driving modes. Section III provides a detailed discussion of our measurement methodologies. The key high-level data statistics are reported in Table I.

Using these measurement datasets, we present a multi-faceted look at the T-Mobile SA-5G deployment from several key perspectives: deployment characteristics, data plane performance, and mobility management. We summarize the key observations and findings below: (1) T-Mobile SA-5G obtains the same cell as the NSA-5G and provides wide outdoor coverage; (2) The connection characteristics and advanced features in SA-5G allow for wider 5G coverage even under extreme radio channel conditions, such as indoors. (3) SA-5G improves the downlink throughput performance but faces challenges with uplink throughput. (4) SA-5G with the low-

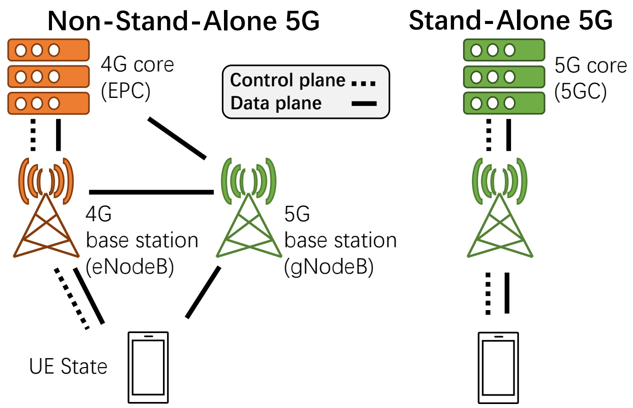


Fig. 1: Overview of NSA and SA-5G architectures.

band deployment achieves the best RTT latency; (5) SA-5G significantly reduces handover occurrence by eliminating dependence on LTE; (6) Reducing 4G connections simplifies SA-5G and reduces performance variance, but may make it less resilient than NSA-5G.

II. Background and Related works

We first provide some background on 5G NR and 5G deployment architectures. We then provide a brief summary of related measurement studies on 5G SA deployment and contrast how our work differs from them.

5G Radio frequencies and Duplex Mode. The advent of 5G technology has introduced wide frequency bands that were previously unexplored, classified into three categories: low-band (<1GHz), mid-band (1∼7GHz), and high-band (24GHz ∼ 71GHz). The low-band frequencies suffer less from propagation fading, making them ideal for wider coverage, but their spectrum is already densely occupied. Conversely, high-band (mmWave) frequencies offer more available bandwidth but are susceptible to limited coverage. In contrast, mid-band frequencies strike a balance between coverage and bandwidth, and have become the preferred bands for 5G deployments.

The frequency bands are divided into channels and operated in two modes: frequency-division duplexing (FDD) and time-division duplexing (TDD). In the FDD mode, dedicated frequency channels are assigned for downlink (DL) and uplink (UL) communications, respectively. In the TDD mode, on the other hand, the same frequency channel is used for both DL and UL communications, but at different times.

5G NSA and SA Deployment Modes. As illustrated in Fig. 1, NSA-5G retains the use of 4G network for control plane operations and the 4G core network, while utilizing the new 5G base stations or 5G radio access network (RAN) infrastructure for data plane transmission. SA-5G operates with a complete 5G stack without relying on any 4G components (see the 3GPP NSA-SA specification [13] for more details). NSA is designed as a transitory deployment mode, with SA-5G as the final deployment mode so as to take advantage of the full potential of the 5G architecture.

Related Work on SA-5G Measurements. There have been a number of initial studies examining and comparing SA and NSA deployments. Two earlier measurement studies [8], [11] of commercial 5G networks, conducted between 2020 and 2021, have identified T-Mobile low-band 5G SA deployments in the US alongside NSA, and provided some preliminary observations of SA-5G low-band performance. Confined to smaller and more controlled environments, a few studies [6], [7], [10] examine the differences between NSA and SA in these environments. While these previous studies have been insightful, they are somewhat limited: conducted either in controlled and lab environments, or measuring only the earlier low-band SA-5G deployments. The study in [12] focuses on the performance of live-streaming video over both NSA-5G and SA-5G deployments in China from a content provider perspective. With no data from the lower layers of the 5G networks, the study provides little insight into how the SA-5G deployment helps improve the user experience over the NSA-5G deployment.

In contrast, our study presents timely measurements obtained in April 2023. This timeline covers the period when T-Mobile set SA-5G as its default 5G radio access architecture, starting transition from NSA-5G to SA-5G. Our work also examines SA-5G from far broader and diverse perspectives, including deployment characteristics, data plane performance, and mobility management. Altogether our work provides a revealing snapshot of the state-of-the-art SA-5G deployments.

III. Measurement tools and methodology

In this section, we describe our measurement methodology, tools, and datasets. Our work focuses on evaluating an operational 5G mobile network in two urban areas using consumer 5G mobile phones and a professional mobile 5G network diagnostics tool. A summary of the collected datasets is provided in Table I.

Measurement Tools. To conduct our measurements, we use several Samsung 5G smartphones (hereafter referred to as user equipment or UE) of two models: S21 Ultras with Qualcomm Snapdragon X60 5G modems and S22 with Qualcomm Snapdragon X65 5G modems. These phones are tethered to a laptop running XCAL [14], a professional mobile network diagnostics and evaluation tool. XCAL's puppeting feature allows for synchronous execution of multiple phones' applications such as the network evaluation tools, Iperf3 and ICMP Ping. XCAL provides in-depth (low-layer) 5G network information, such as the 5G cells and radio bands information, handover operations, 5G channel state, and other operational conditions of the mobile network that the phones are experiencing. The experimental setups for both our driving and stationary tests are shown at the top of Fig. 2.

Measurement Methodology. To provide a fair comparison between the NSA/SA uplink and downlink test cases, we place two (or four) phones side-by-side on each run and execute applications simultaneously using the XCAL tool. Each phone is connected to the T-Mobile 5G network using either the SA-5G mode or NSA-5G mode, and locked into the selected model using the appropriate AT command through the phone's dial screen. This prevents the phones from accidentally switching

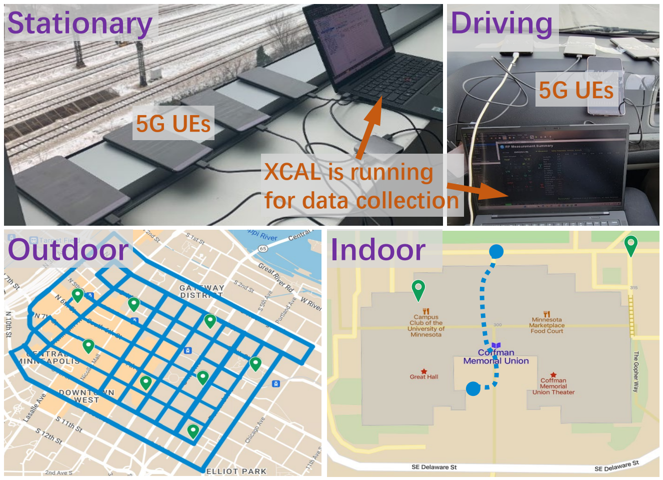


Fig. 2: The top figures depict our measurement setup. The bottom figures show the selected measurement routes and stationary experiment locations (marked by the green icons).

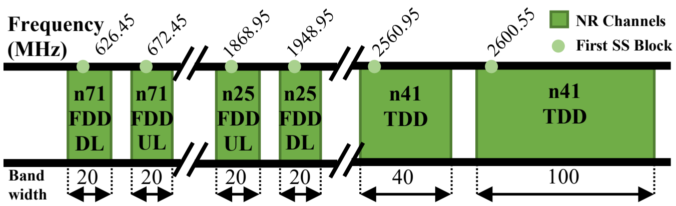


Fig. 3: Detected T-Mobile's 5G channels in our measurements.

between the two deployment modes during the experiments, especially under mobility. We also carefully assign the application tasks to each phone to ensure that they will not compete for the network resources. Given that 5G network configurations are constantly evolving and that available 5G features often depend on UE capabilities, we ensure that the firmware of our testing phones is all up-to-date. To provide a representative space of network coverage, we conduct our tests at several stationary locations and along a driving route in Minneapolis and Chicago. These locations are outlined at the bottom of Fig. 2. This provides a robust snapshot of the network's coverage. We conduct a large number of repeated measurements to improve the reliability of the measurement data collected.

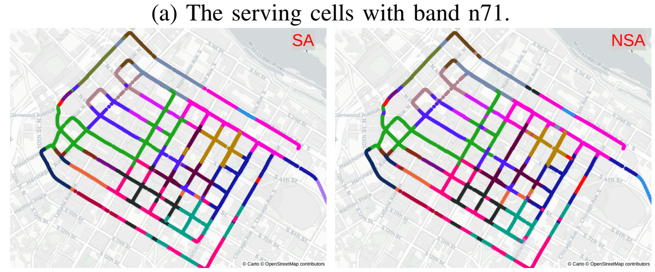
IV. A Multi-Faceted Look at SA-5G vs. NSA-5G

Using the above collected datasets, we now examine SA-5G from multiple perspectives, including deployment characteristics, data plane performance, and mobility management.

A. Deployment Characteristics

Radio Channels. Figure 3 depicts the radio channels detected in the T-Mobile 5G network under study. These channels fall either within the low-band or mid-band frequency ranges. T-Mobile employs two pairs of (DL/UL) channels, each with a bandwidth of 20MHz, one pair in the 5G low-band (n71) and the other in the 5G mid-band (n25), both operating in the FDD mode. It also employs two channels in another 5G

(a) The serving cells with band n71.



(b) The serving cells with band n41.

Fig. 4: Map of connected 5G cells in Minneapolis downtown (about $1km^2$). Each color indicates one unique cell. The left is SA mode, and the right is NSA mode.

mid-band (n41) operating in the TDD mode: one channel has a bandwidth of 40MHz, and the other one is 100MHz.

The deployment of SA-5G is intended to support more flexible 5G channel combinations for *(downlink) carrier aggregation*. Our measurements confirm the use of 5G FDD+TDD and three-channel carrier aggregation used in the T-Mobile SA-5G deployment. This allows for a total downlink 5G bandwidth of up to 160MHz[1]. In contrast, while NSA-5G also supports carrier aggregation, it cannot enjoy such capability of three channel carrier aggregation. This leads to an overall lower downlink bandwidth for the NSA-5G deployment (see Section IV-B on how these affect the end-to-end user experience).

Physical Cells. We map the collected cell IDs during our Minneapolis driving experiments to better understand the radio cell deployment, as shown in Fig. 4. We observe a total of 71 serving cells, with 35 on band n41 and 36 on band n71. Although there are small mismatches at the cell edges due to handovers, we observe that generally the same cell serves both SA-5G and NSA-5G phones at the same location. In other words, we do not find any 5G cells that are dedicated to a specific architecture. This indicates that the same 5G base station (gNodeB) is used for both modes. We thus speculate that wherever it is deployed, the SA-5G outdoor coverage is/will be comparable to that of NSA-5G.

Signal Strength & Power. To examine and compare the signal behavior under two modes, we calculate the power difference between SA and NSA (i.e., $\Delta_{power} = Power_{SA} - Power_{NSA}$) using the *downlink* reference signal received power (ssRSRP) and transmission power of the physical *uplink* channel (PUSCH). Fig. 5 shows a 500-second trace.

[1]The combination of two n41 channels and one n25 channel yield 100MHz+40MHz+20MHz.

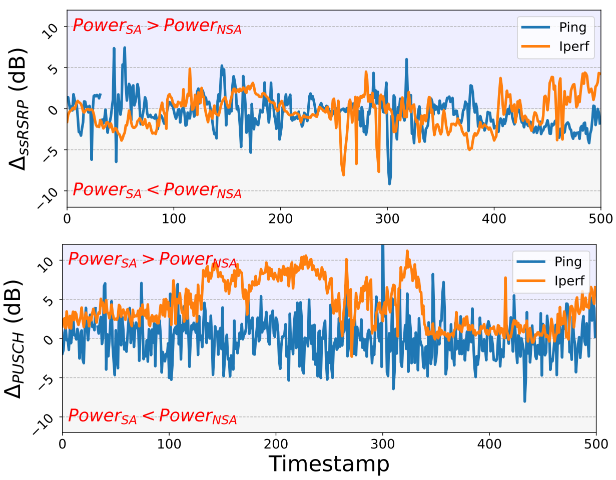


Fig. 5: A 500-second sample trace of ssRSRP (top) and PUSCH power (bottom) when UE runs PING and Iperf. The y-axis calculates the power gap between SA and NSA, where the positive number represents SA using higher power.

For the downlink, we find there is no significant difference in ssRSRP between the SA and NSA deployment modes when UE runs Ping and Iperf measurements. This provides another evidence that the UEs are connected to the same 5G radio antenna (or gNodeB), which uses the same transmission power for DL transmissions.

For the uplink, we observe that Δ_{PUSCH} is consistently larger than 0 when running Iperf. This power difference can even reach up to 10dB (as seen around the 200th seconds of Fig. 5) and 2.6dB on average[2]. This indicates that under the SA-5G mode, a UE is allowed to employ higher transmission power for UL transmissions. One plausible explanation is that the 4G LTE component in the NSA mode occupies a portion of the limited total transmission power of a UE, thus reducing the available power for the 5G UL transmission. This effect is more pronounced during heavy data transmissions such as during the Iperf experiments noted above.

Outdoor-to-Indoor Coverage. We use a case study to further explore the characteristics of SA-5G coverage. We walk from the outside into a building with phones running applications under both the NSA and SA modes. The scenarios and results are illustrated in Fig. 6.

Both phones are connected to the same mid-band (n41) cell when we are outside the building. As we walk into the building, we observe the (DL) ssRSRP drops off, indicating worsening indoor channel conditions. In response, the uplink transmission power is increased to overcome the propagation loss and ensure the gNodeB can receive sufficiently good signals to decode the UL transmissions from UE. In the case of the SA mode, we find that the UE further switches the primary cell to the cell on low-band (n71) to increase the coverage and sets the band n41 cell as the secondary cell, utilizing FDD+TDD carrier aggregation. In contrast, the UE under the

[2]It corresponds to a power ratio of approximately 1.8 times in the absolute value.

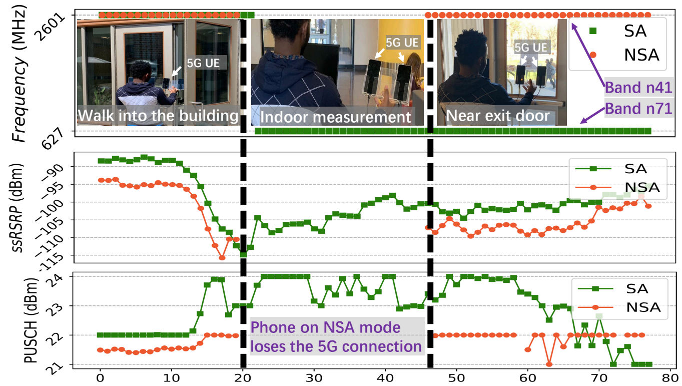


Fig. 6: SA vs. NSA Coverage Case Study: Outdoor-to-Indoor.

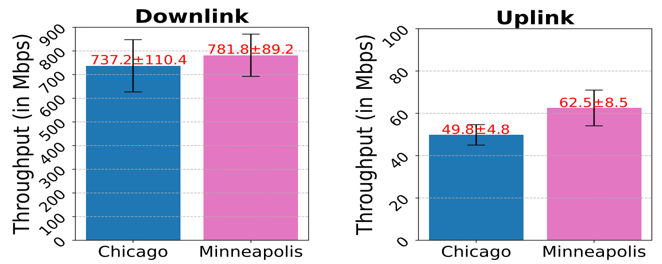


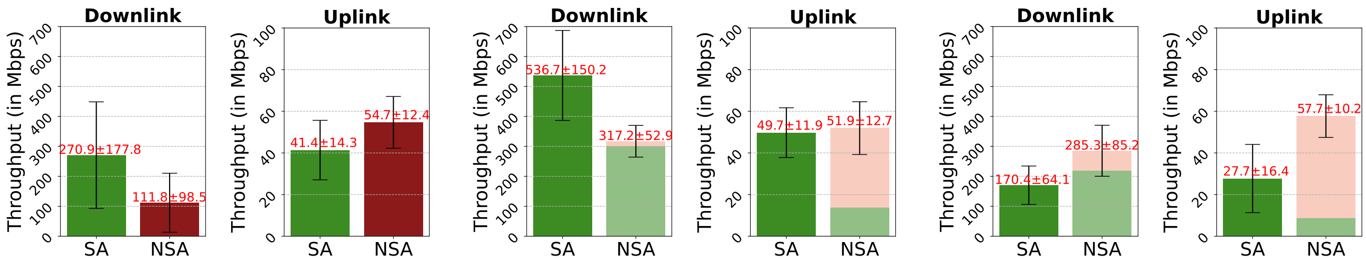
Fig. 7: DL vs. UL throughput performance in Chicago and Minneapolis: stationary with good channel conditions.

NSA mode simply drops off the 5G connection, relying on the 4G LTE alone for data transmission. 5G connectivity is only re-established when we exit the door. We speculate that the reduced 5G uplink power leads to lower coverage. Whereas, by switching from the 5G mid-band channel to the 5G low-band channel, which suffers less physical propagation loss indoors, and by employing the flexible FDD+TDD carrier aggregation, the SA-5G deployment provides much wider 5G coverage and better performance even under such changing and challenging channel conditions.

B. Data Plane Performance

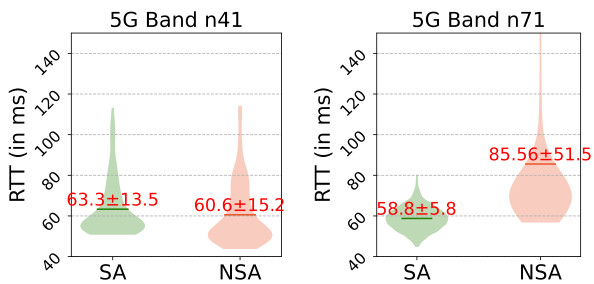
Throughput Performance. Fig. 7 shows the DL and UL throughput performance of SA-5G deployments in Chicago and Minneapolis. The data is collected by the UEs placed in a stationary position near gNodeB without any obstructions (thus under good channel conditions). The results show that T-Mobile SA-5G can achieve up to 800Mbps downlink throughput. In contrast, the uplink throughput is only 50Mbps to 60Mbps or so, about only 7% of the downlink throughput. This asymmetric performance is due to two factors. First, the 5G gNodeB employs carrier aggregation and MIMO technologies for DL transmissions, which are unavailable for UE UL transmissions. Second, in the TDD mode, radio resources (slots) available for UL transmissions are significantly lower.

We further conduct more comprehensive driving experiments in Minneapolis to examine and compare the impact of varying channel conditions on the DL/UL throughput performance of SA-5G and NSA-5G. As shown in Fig. 8a, the downlink throughput in driving mobility scenarios experiences a significant drop compared to the stationary scenarios of

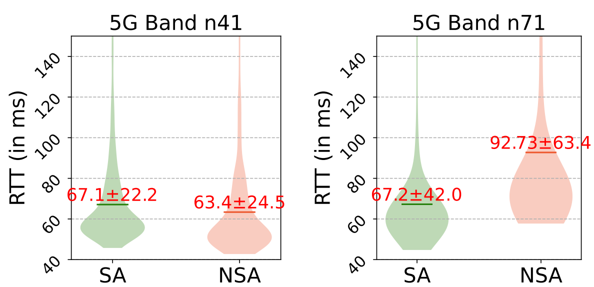


(a) Overall. (b) Good 5G condition (5G CQI>12). (c) Bad 5G condition (5G CQI<8).

Fig. 8: SA-5G DL/UL throughput performance of Minneapolis driving test. Subfigures (b) and (c) break down the results of (a) based on the 5G channel conditions (CQI). The light green and orange color in the NSA mode represents the 5G and 4G share. Note that the channel conditions for 5G do not necessarily represent those of 4G.



(a) Good condition (5G CQI>12)



(b) Bad condition (5G CQI<8)

Fig. 9: 5G latency performance of under different CQIs evaluated by RTT. The contour represents the distribution, and values indicate (mean±variance).

Fig. 7. Whereas the uplink throughput does not degrade very much. To help better analyze the observed performance, we further separate the results under ”good” vs. ”bad” channel conditions based on CQIs (channel quality indicators). Fig. 8b and Fig. 8c show that in terms of downlink throughput SA-5G outperforms NSA-5G under good channel conditions, whereas it underperforms NSA-5G under bad channel conditions. In contrast, the UL throughput performance of SA-5G is always higher than that of the 5G uplink used in the NSA mode (the light green areas) under both good and bad (5G) channel conditions. Nonetheless, the SA-5G UL throughput performance is consistently lower than the *combined* 4G and 5G UL throughput performance. This is because NSA-5G relies on the more reliable 4G connection for a majority of UL data transmissions, especially when the 5G channel condition becomes poorer.

Latency Performance. We further analyze the latency performance of SA-5G vs. NSA-5G by conditioning on the 5G band used. Fig. 9 shows the round trip time (RTT) performance measured via Ping packets under different 5G channel conditions. We find that SA-5G using low-band (n71) under good channel conditions (see Fig. 9a) achieves the best overall average latency performance, reducing latency by around 30.1% compared to the NSA-5G deployment using the same 5G band, but also outperforms NSA-5G under bad 5G channel conditions. This could be attributed to the dedicated DL/UL channels used in the FDD mode as well as the improvements in the SA-5G core networks. Conversely, we observe that the SA deployment with 5G mid-band (n41) is slightly inferior to the corresponding NSA deployment. This may be because the NSA-5G has additional 4G LTE connections and the mid-band of SA-5G still requires further optimization.

In addition, SA-5G shows overall smaller RTT variations than NSA-5G. However, 5G channel condition has a more significant impact on SA-5G than NSA-5G. A comparison of Fig. 9a and Fig. 9b shows that SA-5G's performance drops more significantly than that of NSA-5G. We speculate that this is likely due to the more reliable 4G channel used in NSA-5G. NSA-5G with band n41 yields the best average latency performance under poor 5G channel conditions.

C. Mobility Management

Handover. Ensuring uninterrupted connectivity for mobile devices as they move around in a mobile network is crucial. The procedure that UE switches its attachment from one base station to another is known as a *handover*. Using our measurement datasets, We examine handover performance under SA-5G and NSA-5G.

Table II presents the frequency of handover occurrences for various deployments, along with their corresponding *radio duration*[3] and *total duration*[4]. We see that SA-5G experiences a lower rate of handover occurrences, about 60% less than NSA-5G. Its handovers also exhibit less variance. This can be attributed to its simpler architecture, i.e., no need for a 4G base station as the anchor (recall Fig. 1).

[3]Defined as the duration between the base station request with the 'RRC-Reconfiguration' message and the UE response with the 'RRC-Reconfig-Complete' message.

[4]Defined as the duration between the time UE sending the last measurement report and the time the whole handover procedure is successfully completed.

TABLE II: Overall handover statistics. Duration measured in ms.

	HO Occurrence	Radio duration	Total duration
SA41	**139**	48.50±**4.54**	92.70±**18.07**
NSA41	347	**21.05**±10.55	**84.20**±34.06
SA71	**136**	41.81±**4.76**	89.30±**17.35**
NSA71	341	**18.58**±8.22	**70.42**±22.26

TABLE III: Breakdown handover types in NSA deployment.

NSA HO Types (Occurrence)		Radio duration	Total duration
NSA41	4G-4G (2)	42.50±0.71	97.50±2.12
	Add-5G (54)	14.85±4.40	56.72±11.59
	NSA-4G (97)	22.92±4.66	104.34±37.29
	NSA-5G (143)	14.26±3.76	73.59±26.76
	Drop-5G (51)	42.24±3.35	104.25±29.01
NSA71	4G-4G (1)	43.00±0.00	93.00±0.00
	Add-5G (60)	13.58±3.23	57.19±11.43
	NSA-4G (96)	20.33±3.48	80.83±15.92
	NSA-5G (131)	12.96±3.00	62.68±21.56
	Drop-5G (53)	34.49±1.46	85.00±26.12

The table indicates that SA-5G incurs a slightly longer handover duration than NSA-5G. This is slightly misleading, as NSA-5G experiences many ”lightweight” handover events, which pull down the average values. To illustrate, Table III presents the different types of handovers that occurred in the NSA deployment, including simple 4G handover (4G-4G), attach 5G gNodeB to the 4G anchor eNodeB (Add-5G), 4G anchor eNodeB changes under dual connection (NSA-4G), 5G gNodeB handover under the same 4G eNodeB anchor (NSA-5G), and dropping the 5G connection (Drop-5G).

From the breakdowns in the table, we see that the shaded types of NSA handovers (i.e., 4G-4G, NSA-4G, Drop-5G) require longer total durations. These types of handover involve the 4G anchor eNodeB, yielding more complex signaling procedures. Lastly, we also want to note that these handover events can cause a bigger disruption in the real application performance than the handover execution time [15].

V. Conclusions and Future Work

This paper provides a multi-faceted look at the T-Mobile Stand-Alone (SA) deployment in the US from multiple perspectives, including deployment characteristics, data plane performance, and mobility management. Through a thorough in-field measurement study conducted in two US cities, we also compare the performance of T-Mobile's SA-5G and NSA-5G deployments. We find that SA-5G yields significant improvements in many areas; but in other areas such as uplink throughput performance and latency performance under poor 5G channel conditions, SA-5G yields no performance improvements, or even worse performance, over NSA-5G. Our study not only provides a valuable snapshot of the state-of-the-art 5G SA deployments, but also produces useful insights on the comparative performance of SA-5G vs. NSA-5G from the UE perspective. As many mobile operators have started, or are contemplating, rolling out SA-5G deployments, we believe our study will help them improve future SA-5G deployments. As our current study focuses primarily on the SA-5G RAN and data plane performance issues, there are still many questions regarding the 5G RAN control plane and 5G core networks that need to be explored. These will be left to future studies.

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