A Peek into 5G NSA vs. SA Control Plane Performance

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ABSTRACT

The Stand-Alone (SA) 5G deployment mode promises many benefits over the Non-Stand-Alone (NSA) 5G mode, such as improved throughput, lower latency, and more architectural flexibility, to better support future emerging applications such as AR/VR, IoT, and teleoperated driving. These promised improvements also extend to the control plane operations of 5G-SA, such as attachment/registration procedures to mobile networks, mobility, and security management to provide better user quality-of-experience (QoE). Most of the existing work explores the data plane and end-to-end performance of 5G. In this paper, we investigate and quantify the performance differences in the control plane of 5G-SA compared to 5G-NSA. Our results indicate that 5G-SA mostly has a worse (*i.e.,* slower) control performance (by 16.6% for attachment/registration, PDU session establishment and 64.3% RRC procedure), unlike expectations, raising questions about current (virtualized) 5G-SA deployment and core network functionality placement.

CCS CONCEPTS

• **Networks** → **Mobile networks**; **Network measurement**; **Network performance analysis**; **Wired access networks**;

KEYWORDS

5G, Stand-Alone (SA), Non-Stand-Alone (NSA), Network Measurement, Control Plane, User Plane, Signaling, Performance, Dataset

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1 INTRODUCTION

Control Plane (CP) operations in cellular networks are essential for users' Quality of Experience (QoE); when a mobile device is undergoing control plane communications, the ongoing voice/data session is halted until the control plane operations are done. This

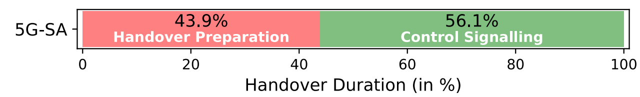

Figure 1: Significance of Control Plane in HO

process, while disruptive, is necessary to ensure overall QoE. For instance, when a user is moving, voice/data flowing from a User Equipment (UE) via the Base Station (BS)[1] to the core network[2] must be redirected to a new BS with better signal quality. A key mobility management procedure (*i.e.,* Handover (HO)) is triggered to switch between BSs. During a HO, the control plane signaling overhead accounts for ∼56% of the HO duration time (see Fig. 1), which directly impacts the upper-layer and users' QoE by halting application voice/data [22]. HOs happen frequently, for example, during an 8-minute walk, we experienced 31 HOs, (see [26] for more details and different types of HOs).

We classify control plane operations (*i.e.,* signaling) based on the entities involved as: (i) from a mobile device (*i.e.,* UE) to its serving cell (or BS), or (ii) from the UE to different core network components (see §2 for more details). Additionally, a UE interacting with different core network deployments could experience different control plane performance. As shown in Fig. 2, there are generally two 5G deployment modes: 5G Non-Standalone (5G-NSA) and 5G Standalone (5G-SA). In 5G-NSA, the 4G eNodeB provides all control plane connectivity while the data plane goes through the 5G gNodeB, and both to the 4G core EPC; while in 5G-SA, the control and data plane go through the gNodeB to the 5G Core. As a result, the control plane signaling execution time between UE to the BS and core could be different in 5G-SA vs. 5G-NSA. For example, HOs can occur on average every 400 m in 5G-NSA and 900 m in 5G-SA [22]. This is because, in 5G-NSA there are HOs between 4G-4G, 4G-5G, and 5G-5G. This emphasizes the impact and

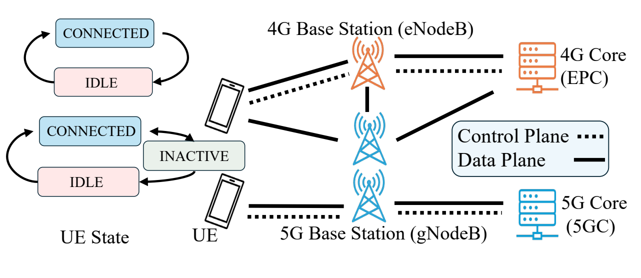

Figure 2: 5G-NSA vs. 5G-SA Architecture

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[1] evolved Node B (eNodeB) in 4G and next Generation Node B (gNodeB) in 5G [see 3GPP TS 38.331 [4] for more details].

[2] Evolved Packet Core (EPC) in 4G and 5G Core Network (5G Core) in 5G [see 3GPP TS 24.501 [5] for more details].

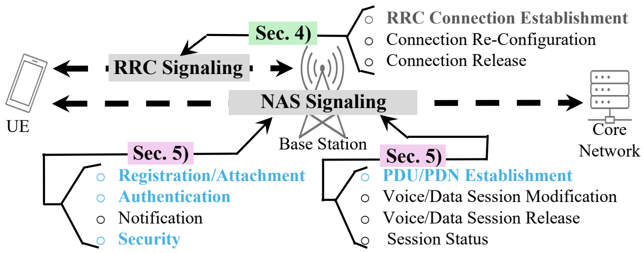


Figure 3: 4G/5G Control Plane Taxonomy

Table 1: 4G/5G Control Plane Message Equivalence

4G	5G
RRC Procedure	
RACH Procedure	
Attachment	Registration
Detachment	De-Registration
PDN Connection	PDU Connection
Authentication	
Security Mode	

Table 2: Statistics of The Collected Data.

Operator	T-Mobile
Mode	5G-NSA, 5G-SA
Data Size	1.1 GB
Data Traces	224 hours

rapid escalation of control plane operations on users' QoE. Another fundamental architectural deployment difference between 5G-NSA and 5G-SA is that 5G-NSA still relies on the legacy 4G EPC in which all the network functions are performed by dedicated hardware boxes. However, 5G-SA is deployed with the "new" 5G Core – all network functions can be virtualized [8, 11, 32], which means that mobile operators can easily replicate infrastructure and at a much lower cost than the hardware boxes utilized by the 4G EPC.

This raises important "yet unanswered" questions: (1) *What is the performance of the control plane of 5G-SA compared to 5G-NSA? Does the gNodeB in 5G-SA provide better control plane performance than the eNodeB in 5G-NSA as claimed [1, 21, 26]?* (see §4). With 5G-SA envisioned to optimize these control plane procedures using techniques such as virtualization and Software Defined Networks (SDNs), can we say whether (2) *today's 5G-SA is really virtualized or not?* For the signaling messages between the UE and the core network, some procedures may hit (*i.e.,* be processed by) certain core network functions, while others may not. We thus ask: (3) *How can we infer the control plane interaction time of a UE with the different network functions in the 4G and 5G core?* (see §5). This leaves open the exploration of the placement of different components in the 5G-NSA and 5G-SA mobile architectures. (4) *Is the current placement optimized or can it be improved?*

Most of the existing work [17, 20, 22, 25–29, 33, 34] focuses on data plane performance between 5G-SA and 5G-NSA and may briefly touch on control plane operations. In particular, they model and measure the control plane traffic, but largely fall back to utilizing statistical models rather than live commercial measurements from deployed mobile operators. In this work, we examine the control plane performance in 5G-NSA and 5G-SA for T-Mobile as currently it is the only operator in the United States with 5G-SA deployment. We investigate the claims of 5G-SA having better performance by quantitatively understanding the new improvements (if any) and performance trade-offs between 5G-NSA and 5G-SA.

Contributions. Our work's contributions are the following:

• We fill the gap in the existing literature by contributing to the understanding of commercial 5G with our comparative analysis of control plane performance in 5G-NSA and 5G-SA.

• Through detailed UE message interactions, we infer and quantify the time it takes for a UE to interact with different core network components in 4G and 5G, providing insights about the various network functions and their performance characteristics.

• We will release our data at https://github.com/HotMobile2025-NSA-SA-ControlPlane, providing the research community with real commercial 5G control plane data to foster future research.

• Modeling control plane traffic and studying their time/delay implications can provide insight into the realization of improvements going from 5G-NSA to 5G-SA. This greater understanding of network function placement and performance may open new research into core network function placement and colocation.

Paper Structure. We discuss control plane events in §2, and our methodology is presented in §3. Messages between the UE and BS are discussed in §4, and with the core in §5. Related work is presented in §6. Finally, §7 concludes the paper with a discussion of implications and future work.

2 4G AND 5G CP EVENTS BACKGROUND

As illustrated in Fig. 3, both 4G and 5G's control plane messages can be classified according to the interacting entities: (i) between a UE and a BS, and (ii) between a UE and the core network. In Table 1, we show the critical control plane messages our study focuses on and the equivalence between 4G and 5G. Similar to 4G, two types of signaling messages exist in 5G: Radio Resource Control (RRC) and Non-Access Stratum (NAS) signaling messages.

i) Signaling between the UE and BS (§4). In both 4G and 5G, the RRC messages are handled and managed by the RRC layer, which is responsible for triggering different *RRC State* changes. Unlike 4G in which two RRC states exist (*RRC_IDLE* and *RRC_CONNECTED*), 5G introduces an intermediate *RRC_INACTIVE* state. To send/receive data on the network, a UE must be in *RRC_CONNECTED* state. When the UE is in the *RRC_IDLE* state, its state information is removed from the BS and the core network. The *RRC_INACTIVE* state is anticipated to help reduce latency overhead as the UE transitions to the *RRC_CONNECTED* state [4] by maintaining the UE state at the core. Hence, when the UE is in *RRC_INACTIVE*, it only needs to re-establish its state at the BS. We note that we have not "yet" observed the *RRC_INACTIVE* state deployed by T-Mobile at our measurement locations.

ii) Signaling between the UE and Core Network (§5). In 4G, the NAS messages allow signaling between the UE and the Mobility Management Entity (MME) EPC network function. In 5G, they allow signaling between the UE and the Access and Mobility Management Function (AMF) and Session Management Function (SMF). These messages are crucial for establishing and maintaining connectivity sessions between the UE and core network at all times [6, 7]. They govern several events like HOs, beam failures, scheduling requests, downlink/uplink data arrival, *etc.*

3 MEASUREMENT APPROACH

Measurement Tools. We use four Samsung Galaxy phones subdivided by two models; the S21 Ultra (S21U) and S23. These phones are connected via USB/USB-C to a laptop running XCAL [2], a professional mobile network diagnostics and monitoring tool. XCAL lets us collect detailed control/signaling plane and data/user plane information directly from the phone's chipset. 75% of the control plane signaling procedures are triggered when the phone switches from offline to online [31]. To measure these procedures, we leverage Tasker [15] and AutoInput [23], both scheduling and manipulation phone apps. AutoInput lets us configure commands *i.e.,* turning Airplane Mode ON/OFF, which in turn enables us to trigger the procedures we wish to measure. Tasker enables us to schedule tasks based on context like time, date, and events providing a means of setting up recurring experiments.

Methodology for Data Collection. With our tools, we collect data at three locations in Minneapolis, MN. At each location, we place two phones side-by-side to ensure fair comparison and similar channel conditions. To prevent our phones from automatically switching between deployment modes during testing, we use Samsung's service code (*#2263#) to selectively lock each phone into either 5G-SA or 5G-NSA mode. We trigger the procedures by using Tasker and AutoInput to turn Airplane Mode OFF/ON and schedule these to run 24/7 every 2 minutes while running XCAL. Our measurements cover more than 224 hours of measurement in 7 days over the three locations. Our dataset is summarized in Table 2.

Primary Challenge. To understand the execution time of the control plane procedure between a UE and various core components, approximate or complete knowledge of the message sequence of each procedure is imperative. In this study, we lack visibility into the commercial operator. This presents a major challenge. To overcome this challenge, we rely on the control plane messages captured at the UE and assume the sequence diagrams represented in [9, 10, 12] provide a close approximation. This is because, based on our dataset, the control plane messages found in our observed experiments to and from the UE match the order of these different sequence diagrams for each procedure.

4 WHAT IMPROVEMENT (IF ANY) DOES 5G-SA PROVIDE OVER 5G-NSA

In this section, we utilize our dataset to quantitatively examine and compare the control plane signaling procedures execution times between the UE and the BS in both 5G-NSA and 5G-SA.

Quantification Approach. Control plane procedures can either be triggered/initiated by the UE and terminate when the network sends a confirmation to the UE, or triggered/initiated within the core network. For instance, the Attachment/Registration and RRC procedures are initiated by the UE, whereas the Authentication and Security procedures are initiated within the core network. The Packet Data Network (PDN) connection is initiated within the EPC, while the equivalent Packet Data Unit (PDU) connection is initiated by the UE in 5G. In the UE-triggered procedures, we can precisely quantify the procedure execution delay. For the procedures triggered within the core, we closely approximate an upper bound interaction time.

RRC Connection. A UE must transition from *RRC_IDLE* mode to *RRC_CONNECTED* mode before sending/receiving any voice/-data via the cellular network. The RRC connection procedure is always initiated by the UE, but can be triggered by the network.

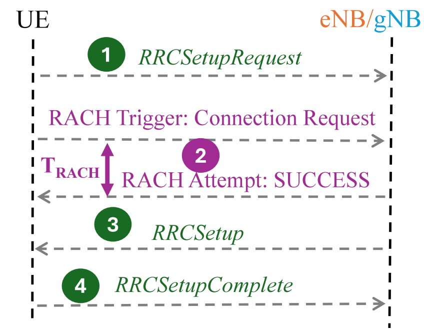


Figure 4: RRC Connection Procedure Call Flow

For example, if a UE starts an application to browse the internet or to send an email, it must trigger the RRC connection procedure. If the BS has incoming SMS or incoming voice calls, it must trigger the RRC connection procedure by paging the UE. The RRC connection procedure sequence diagram is shown in Fig. 4. In both 4G and 5G, the UE triggers the RRC connection procedure by sending the *RRCSetupRequest* message (see step ❶). The UE must specify the reason for establishing a connection with the BS. The content of the *RRCSetupRequest* message contains an *RRC Establishment Cause* in which the UE has to specify the access category. In 4G, 3GPP specifies only six *RRC Establishment Causes*, whereas 11 are specified in 5G [3] [4]. In this study, we focus on the "data" establishment cause. After sending the *RRCSetupRequest* message, the UE waits to receive the *RRCSetup* message (see step ❸) containing critical parameters such as the available bands, channel bandwidth, and different security modes required to communicate with the BS. After successfully applying the configurations, the UE sends the *RRCSetupComplete* (see step ❹) as confirmation to the BS. Next, we quantitatively study the RRC connection setup time comparing 5G-NSA and 5G-SA.

Fig. 5 shows the distribution of the RRC connection execution time in 5G-NSA and 5G-SA. We see the RRC procedure delay time in 5G-SA (with the gNodeB) is higher (*i.e.,* worse) than in 5G-NSA (with the eNodeB). Quantitatively, the RRC procedure time in 5G-SA is 47.7% longer when compared with 5G-NSA. We also find that the variability of this time in 5G-SA is larger (by 74% on average) compared to 5G-NSA.

Random Access Procedure. Although the RRC procedure with both the eNodeB and gNodeB is mostly unchanged, there are some

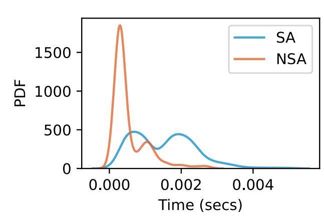


Figure 5: RRC Delay

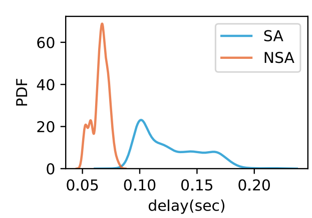
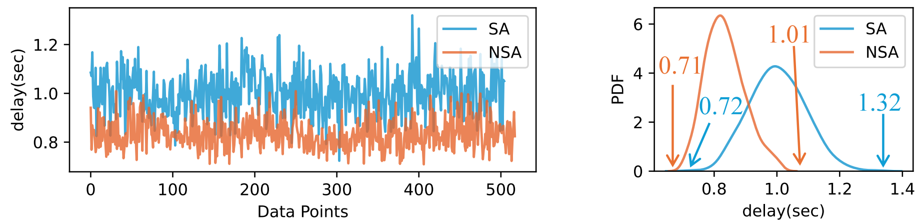


Figure 6: RACH Delay

[3]The *RRC Establishment Cause* ranges from emergency, to high priority access, to SMS data, voice call, video call, *etc.*



(a) 4G/5G Attachment and Registration Procedure . **(b) 4G/5G Initial Procedure.**

Figure 7: Time series and distribution plots of the Initial Attachment and Registration procedures in 4G and 5G.

unique structural characteristics. Unlike 5G-NSA, 5G-SA introduces the Control/User Plane Separation (CUPS) to enable independent scaling of the gNodeB hardware while enabling a cloud-based flexible distributed deployment structure to minimize latency [3]. For the UE to receive the *RRCSetup* message, uplink and downlink synchronization between the UE and the gNodeB Central Unit (gNodeB-CU) needs to occur via the so-called *Random Access Channel (RACH)* procedure [30] (see step ❷ in Fig. 4). Therefore, to further understand why the RRC procedure time in 5G-SA is longer than that of 5G-NSA, we also quantify the delay in the RACH process – the time between the *RACH Trigger: Connection Request* message sent by the UE and the *RACH Trigger: Success* sent by the BS, *i.e.,* T_{RACH} in Fig. 4.

As shown in Fig. 6, we find that: (i) not only is the distribution of the RACH process closely aligned with the distribution of the RRC Connection time in both 5G-SA and 5G-NSA, and (ii) the RACH process delay in 5G-SA is also higher (by 64.3% on average) than in 5G-NSA. Also, note that T_{RACH} precisely quantifies the time it takes for a UE to interact with the eNodeB and gNodeB (hereafter referred to as T^{4G}_{eNB} and T^{5G}_{gNB}) in 5G-NSA and 5G-SA respectively. We suspect that these results are due to the wider channel bandwidth in the gNodeB (100 MHz in our study) when compared with the eNodeB (20 MHz in our study). To digress, unlike in 5G-NSA, in 5G-SA, both the UE and gNodeB need to sweep through the whole (100 MHz) channel bandwidth to select the best beam to synchronize and receive/send *RRC* messages. Thus, the gNodeB needs to process a larger number of RACH access attempts and retries, leading to longer RACH process times. Furthermore, we suspect that the greater latency variability in 5G-SA is potentially due to CUPS, network function virtualization overhead, or RACH message abundance.

5 INFERRING CP DELAY BETWEEN UE AND CORE NETWORK

In this section, we quantify the execution delays of control plane signaling procedures between the UE and various core network components. We start with the UE-triggered procedures and then study the procedures triggered within the core network to infer the delay between a UE and different component of the core network.

Attachment/Registration Procedure. Fig. 7a and Fig. 7b depict the time series and distribution plots of the latency incurred during the Attachment and Registration procedures with the 4G and 5G cores. Surprisingly, the 5G-SA Registration procedure consistently incurs a longer latency (*i.e.,* performs worse) compared to the 5G-NSA (*i.e.,* 4G) Attachment procedure. While the mean 4G Attachment delay is 0.835 seconds, the mean SA Registration latency is 1.001 seconds, a 16.6% increase. Our results do not show a clear improvement of 5G-SA over 5G-NSA in this regard. To further investigate, we quantify the time it takes for a UE to interact with the eNodeB/gNodeB and with the different core network functions during other signaling procedures.

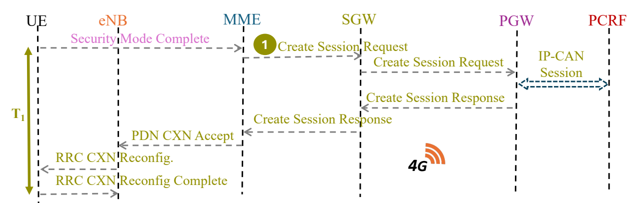


Figure 8: 4G PDN Connection Procedure Call Flow Diagram

PDN/PDU Connection Establishment Procedure. The PDU setup procedure provides end-to-end (E2E) user plane connectivity between the UE and the core network when using the 5G Core network. The equivalent when using the EPC is the PDN setup procedure. As stated above, the PDU connection is initiated by the UE, while the PDN connection is initiated within the core network. Consequently, we define the upper bound PDN connection establishment time in 5G-NSA as T_1 shown in Fig. 8, while we are able to precisely quantify the PDU connection time as shown in Fig. 9.

Fig. 10a shows the PDU and PDN Connection Establishment delays in 5G and 4G. We see that on average 5G has a delay of 0.55 seconds, which is higher than 4G's delay of 0.44 seconds. Given the similar standard deviation, this shows Session Establishment in

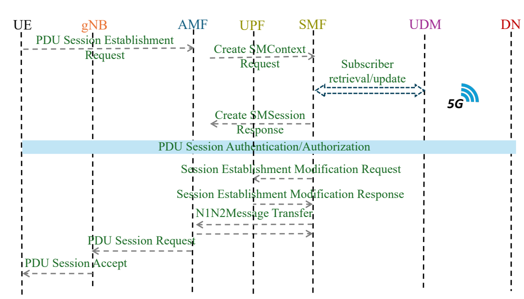
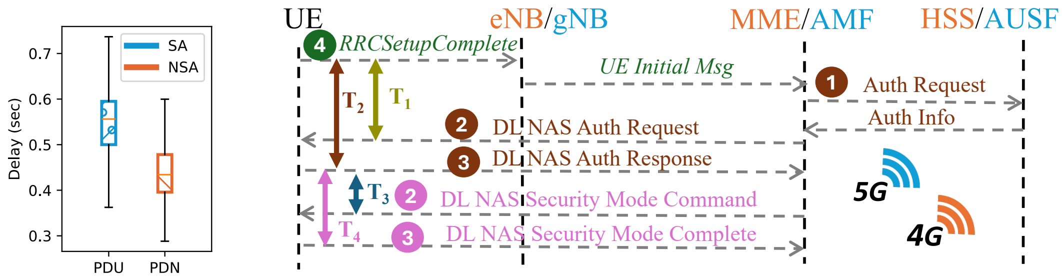


Figure 9: 5G PDU Session Establishment Call Flow Sequence Diagram



(a) PDU/PDN Connection Establishment Delays.

(b) Authentication and Security CP Procedure call flow diagram in 4G and 5G.

Figure 10: Inferring CP Delay Between UE and the Core Network. Fig(a) shows the upper bound PDN connection time and measured PDU connection time. Fig(b) shows the call flow diagram used to estimate the UE's interaction time with various core network functions in 4G & 5G.

Table 3: Inferring the CP delay of the UE's Interaction with Various Core Network Functions in 4G and 5G (in seconds).

Technology	T_1	T_2	T_3	T_{HSS}	T_{AUSF}
5G	0.11±0.01	0.17±0.05	0.04±0.03	N/A	0.12±.05
4G	0.16± 0.03	0.31±0.04	0.04±0.05	0.07±0.04	N/A

5G is consistently about 25% worse compared to 4G. Furthermore, while we are able to explicitly capture PDU Session Establishment messages in 5G, we can only estimate an upper bound for the time taken for PDN Connection Establishment in 4G. This indicates that the actual performance difference may be steeper (favoring 4G).

Authentication and Security Procedure. Lastly, Fig. 10b shows the call flow sequence diagram of the Authentication and Security procedure and the interaction with the different core network functions involved. Notice that Authentication is initiated by the MME in 4G and AMF for 5G (see step ❶) while the security is initiated by the MME (4G) and AMF (5G) (see step ❷). In addition, this process involves the Home Subscriber Server (HSS) and Authentication Server Function (AUSF). Therefore, we quantify the delay of the upper bound of the Authentication procedures as T_2^{4G} and T_2^{5G}. We also define the delay interaction with the eNodeB/gNodeB and MME/AMF as $T_3^{4G} = T_{eNB} + T_{MME}$ and $T_3^{5G} = T_{gNB} + T_{AMF}$. Subsequently, we define $T_1^{4G} = T_{eNB} + T_{MME} + T_{HSS}$ and $T_1^{5G} = T_{gNB} + T_{AMF} + T_{AUSF}$. Clearly, $T_{HSS} = T_1^{4G}$ - T_3^{4G} and $T_{AUSF} = T_1^{5G}$ - T_3^{5G}.

Table 3 shows the mean and standard deviations of T_1, T_2, T_3, T_{HSS}, and T_{AUSF} in 4G and 5G. In the table, the shaded times indicate better (lower) delays. We see that $T_1^{5G} < T_1^{4G}$, and $T_2^{5G} < T_2^{4G}$. We suspect that during 4G authentication the HSS is only consulted to generate the authentication vectors and does not make a decision on the authentication results. Meanwhile, in 5G authentication, the AUSF processes the UE's response and then makes the final decision on authentication [13]. As a result, processing by the AUSF takes longer than the HSS, as is also confirmed in our results as $T_{AUSF} > T_{HSS}$ (see T_{HSS} and T_{AUSF} in Table 3).

6 RELATED WORKS

5G Measurements: Since the deployment of 5G, numerous measurement studies have attempted to understand the characteristics of 5G systems and their implications on application design. These studies include research conducted in China [33], the United States [16, 19, 22, 26–28], and Europe [17, 18, 20]. Several studies have also provided insights into various aspects of 5G deployment modes (5G-SA vs. 5G-NSA). Hassan *et al.* [22] and Narayanan *et al.* [28] explored different cellular radio bands (low, mid, and high), power consumption, and application QoE. Rischkie *et al.* [29] quantified the one-way download and upload performance in 5G campus networks for both 5G-SA and 5G-NSA. Mohamed *et al.* [25] evaluated the comparison in the indoor environment. Fezeu *et al.* [19] investigated the performance of the data plane and relevant factors. In our work, we focus on comparing the behavior of 5G-NSA and 5G-SA architectures with emphasis on the control plane and some additional exploration of the data plane.

Control Plane Study: Xu *et al.* [33] provides insights on the potential challenges of increased coordination complexity due to denser 5G gNodeBs in 5G-SA. [14, 24] provide modeling of control events within the control plane due to their inaccessibility to the general public. Several works [20, 22, 33, 34] study the impact of HO that involve the RRC procedure on application performance. Our study provides a quantitative analysis of a broader set of control plane procedures, including Attachment and Registration, RRC connection, Authentication and Aecurity, and PDN/PDU connection.

7 CONCLUSIONS, IMPLICATIONS, AND FUTURE WORKS

Is 5G-SA really virtualized? In this work, we measured and examined in detail the performance differences of control plane operations in 5G-NSA and 5G-SA. We find that except for when authenticating using the AUSF vs. the HSS, 5G-SA has worse control plane performance. Additionally, 5G-SA was 16.6% slower (*i.e.,* worse) in the UE's attachment/registration procedure than 5G-NSA. Similarly, 5G-SA's PDU session establishment is slower than the 4G's PDN session establishment in 5G-NSA. Finally, we note that 5G-SA's RRC procedure is 64.3% slower from the abundance of RACH messages due to the wider bandwidth scans. As a result, based on these measurements and data, we conclude that the current 5G-SA core may exist as a translation layer in some form relative to the current 5G-NSA, with a full 5G-SA yet to be virtualized. We suspect the virtualization of the 5G core network functions will indeed bring about improvements in control plane signaling message, and as a result, the users' QoE.

Future works may go into greater depth on more obscure messaging procedures, formalizing the different procedures into equations extrapolating the distance between entities in EPC/5G Core core functions. Additional experiments may expand the number of operators, locations, and experiments. However, in this study we were restricted to only one operator's realization of 5G-SA in this study due to the fact that in the United States, to date, only T-Mobile has deployed 5G-SA. Other work may examine the effects of placing different network functions in the 5G Core to maximize control plane and thus E2E performance. For example, one may conduct speculative analysis of which network functions can be co-located to enhance mobile user experience.

ETHICAL CONSIDERATIONS

This study was carried out by the authors, paid, volunteer graduate and undergraduate students. No personally identifiable information (PII) was collected or used, nor were any human subjects involved. Our study complies with the customer agreements of all 5G mobile operators and will not raise ethical issues.

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REFERENCES

[1] 2021. Control Plane and User Plane Separation (CUPS) Data Sheet.
[2] 2022. Accuver XCAL.
[3] 3GPP. 2018-07. TS 38.401 V15.2.0 - 5G; NG-RAN; Architecture description.
[4] 3GPP. 2020-07. TS 38.331 version 16.1.0 - 5G; NG; Radio Resource Control (RRC); Protocol specification.
[5] 3GPP. 2020-08. TS 24.501 version 16.5.1 - 5G; Non-Access-Stratum (NAS) protocol for 5G System (5GS); Stage 3.
[6] 3GPP. 2022-05. TS 24.301 V17.6.0 - Universal Mobile Telecommunications System (UMTS); LTE; 5G; Non-Access-Stratum (NAS) protocol for Evolved Packet System (EPS); Stage 3. https://www.etsi.org/deliver/etsi_ts/124300_124399/124301/17.06.00_60/ts_124301v170600p.pdf.
[7] 3GPP. 2022-05. TS 24.501 V16.5.1 - 5G; Non-Access-Stratum (NAS) protocol for 5G System (5GS); Stage 3. https://www.etsi.org/deliver/etsi_ts/124500_124599/124501/16.05.01_60/ts_124501v160501p.pdf.
[8] 3GPP. 2022-08. 5G System Overview. https://www.3gpp.org/technologies/5g-system-overview.
[9] alinSamson. 2021. YateBTS. https://yatebts.com/documentation/concepts/5g-core-network/
[10] Author. 2024. 5G SA Registration. https://www.techplayon.com/5g-nr-sa-registration-attach-call-flow/
[11] Michael Begley and et al. [n. d.]. Virtualized 5G RAN: why, when and how?
[12] Catalina Bors. 2020. YateBTS. https://yatebts.com/solutions_and_technology/lte-call-flow-explained/
[13] CableLabs. 2019. *A Comparative Introduction to 4G and 5G Authentication*. https://www.cablelabs.com/insights/a-comparative-introduction-to-4g-and-5g-authentication
[14] Dima Dababneh, Marc St-Hilaire, and Christian Makaya. 2015. Data and Control Plane Traffic Modelling for LTE Networks. *Mobile Networks and Applications* 20 (2015), 449 – 458. https://api.semanticscholar.org/CorpusID:34679091
[15] João Dias (joaomgcd). 2009. Tasker for Android.
[16] Rostand A. K. Fezeu, Jason Carpenter, Claudio Fiandrino, Eman Ramadan, Wei Ye, Joerg Widmer, Feng Qian, and Zhi-Li Zhang. 2023. Mid-Band 5G: A Measurement Study in Europe and US. *arXiv preprint arXiv:2310.11000* (2023).
[17] Rostand A. K. Fezeu, Claudio Fiandrino, Eman Ramadan, Jason Carpenter, Daqing Chen, Yiling Tan, Feng Qian, Joerg Widmer, and Zhi-Li Zhang. 2024. Roaming across the European Union in the 5G Era: Performance, Challenges, and Opportunities. In *IEEE INFOCOM 2024 - IEEE Conference on Computer Communications*. 2378–2387. https://doi.org/10.1109/INFOCOM52122.2024.10621234
[18] Rostand A. k. Fezeu, Claudio Fiandrino, Eman Ramadan, Jason Carpenter, Lilian Coelho de Freitas, Faaiq Bilal, Wei Ye, Joerg Widmer, Feng Qian, and Zhi-Li Zhang. 2024. Unveiling the 5G Mid-Band Landscape: From Network Deployment to Performance and Application QoE. In *Proceedings of the ACM SIGCOMM 2024 Conference* (Sydney, NSW, Australia) *(ACM SIGCOMM '24)*. Association for Computing Machinery, New York, NY, USA, 358–372. https://doi.org/10.1145/3651890.3672269
[19] Rostand A. K. Fezeu, Eman Ramadan, Wei Ye, Benjamin Minneci, Jack Xie, Arvind Narayanan, Ahmad Hassan, Feng Qian, Zhi-Li Zhang, Jaideep Chandrashekar, and Myungjin Lee. 2023. An In-Depth Measurement Analysis of 5G mmWave PHY Latency and sIts Impact on End-to-End Delay. In *Passive and Active Measurement: 24th International Conference, PAM 2023, Virtual Event, March 21–23, 2023, Proceedings*. Springer-Verlag, Berlin, Heidelberg, 284–312. https://doi.org/10.1007/978-3-031-28486-1_13
[20] Claudio Fiandrino, David Juárez Martínez-Villanueva, and Joerg Widmer. 2022. Uncovering 5G Performance on Public Transit Systems with an App-based Measurement Study. In *Proceedings of the 25th International ACM Conference on Modeling Analysis and Simulation of Wireless and Mobile Systems* (Montreal, Quebec, Canada) *(MSWiM '22)*. Association for Computing Machinery, New York, NY, USA, 65–73. https://doi.org/10.1145/3551659.3559040
[21] Gaurav Gangwal and Kevin Gray. 2023. The 5G Core Network Demystified.
[22] Ahmad Hassan, Arvind Narayanan, Anlan Zhang, Wei Ye, Ruiyang Zhu, Shuowei Jin, Jason Carpenter, Z. Morley Mao, Feng Qian, and Zhi-Li Zhang. 2022. Vivisecting mobility management in 5G cellular networks. In *Proceedings of the ACM SIGCOMM 2022 Conference* (Amsterdam, Netherlands) *(SIGCOMM '22)*. Association for Computing Machinery, New York, NY, USA, 86–100. https://doi.org/10.1145/3544216.3544217
[23] João joaomgcd. 2017. AutoInput – Tasker and Join.
[24] Jiayi Meng, Jingqi Huang, Y. Charlie Hu, Yaron Koral, Xiaojun Lin, Muhammad Shahbaz, and Abhigyan Sharma. 2023. Modeling and Generating Control-Plane Traffic for Cellular Networks. In *Proceedings of the 2023 ACM on Internet Measurement Conference* (Montreal QC, Canada) *(IMC '23)*. Association for Computing Machinery, New York, NY, USA, 660–677. https://doi.org/10.1145/3618257.3624808
[25] Ramy Mohamed, Sofiane Zemouri, and Christos Verikoukis. 2021. Performance Evaluation and Comparison between SA and NSA 5G Networks in Indoor Environment. In *2021 IEEE International Mediterranean Conference on Communications and Networking (MeditCom)*. 112–116. https://doi.org/10.1109/MeditCom49071.2021.9647621
[26] Arvind Narayanan, Eman Ramadan, Jason Carpenter, Qingxu Liu, Yu Liu, Feng Qian, and Zhi-Li Zhang. 2020. A First Look at Commercial 5G Performance on Smartphones. In *Proceedings of The Web Conference 2020* (Taipei, Taiwan) *(WWW '20)*. Association for Computing Machinery, New York, NY, USA, 894–905. https://doi.org/10.1145/3366423.3380169
[27] Arvind Narayanan, Muhammad Iqbal Rochman, Ahmad Hassan, Bariq S. Firmansyah, Vanlin Sathya, Monisha Ghosh, Feng Qian, and Zhi-Li Zhang. 2022. A Comparative Measurement Study of Commercial 5G mmWave Deployments. In *IEEE INFOCOM 2022 - IEEE Conference on Computer Communications*. 800–809. https://doi.org/10.1109/INFOCOM48880.2022.9796693
[28] Arvind Narayanan, Xumiao Zhang, Ruiyang Zhu, Ahmad Hassan, Shuowei Jin, Xiao Zhu, Xiaoxuan Zhang, Denis Rybkin, Zhengxuan Yang, Zhuoqing Morley Mao, Feng Qian, and Zhi-Li Zhang. 2021. A variegated look at 5G in the wild: performance, power, and QoE implications. In *Proceedings of the 2021 ACM SIGCOMM 2021 Conference* (Virtual Event, USA) *(SIGCOMM '21)*. Association for Computing Machinery, New York, NY, USA, 610–625. https://doi.org/10.1145/3452296.3472923
[29] Justus Rischke, Peter Sossalla, Sebastian Itting, Frank H. P. Fitzek, and Martin Reisslein. 2021. 5G Campus Networks: A First Measurement Study. *IEEE Access* 9 (2021), 121786–121803. https://doi.org/10.1109/ACCESS.2021.3108423
[30] Jaeku Ryu. 2011. 5G RACH In a Nutshell. https://www.sharetechnote.com/html/5G/5G_RACH.html
[31] Jaeku Ryu. 2011. 5G/NR - Initial Aattach. https://www.sharetechnote.com/html/5G/5G_CallProcess_InitialAttach.html
[32] Verizon. [n. d.]. Virtualization: What it is and how it's shaping Verizon's 5G network.
[33] Dongzhu Xu, Anfu Zhou, Xinyu Zhang, Guixian Wang, Xi Liu, Congkai An, Yiming Shi, Liang Liu, and Huadong Ma. 2020. Understanding Operational 5G: A First Measurement Study on Its Coverage, Performance and Energy Consumption. In *Proceedings of the Annual Conference of the ACM Special Interest Group on Data Communication on the Applications, Technologies, Architectures, and Protocols for Computer Communication* (Virtual Event, USA) *(SIGCOMM '20)*. Association for Computing Machinery, New York, NY, USA, 479–494. https://doi.org/10.1145/3387514.3405882
[34] Wei Ye, Jason Carpenter, Zejun Zhang, Rostand A. K. Fezeu, Feng Qian, and Zhi-Li Zhang. 2023. A Closer Look at Stand-Alone 5G Deployments from the UE Perspective. In *2023 IEEE International Mediterranean Conference on Communications and Networking (MeditCom)*. 86–91. https://doi.org/10.1109/MeditCom58224.2023.10266621