Unveiling the 5G Mid-Band Landscape: From Network Deployment to Performance and Application QoE

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ABSTRACT

5G in mid-bands has become the dominant deployment of choice in the world. We present – to the best of our knowledge – the first *comprehensive* and *comparative cross-country* measurement study of commercial mid-band 5G deployments in Europe and the U.S., filling a gap in the existing 5G measurement studies. We unveil the key 5G mid-band channels and configuration parameters used by various operators in these countries, and identify the major factors that impact the observed 5G performance both from the network (physical layer) perspective as well as the application perspective. We characterize and compare 5G mid-band throughput and latency performance by dissecting the 5G configurations, lower-layer parameters as well as deployment settings. By cross-correlating 5G parameters with the application decision process, we demonstrate how 5G parameters affect application QoE metrics and suggest a simple approach for QoE enhancement. Our study sheds light on how to better configure and optimize 5G mid-band networks, and provides guidance to users and application developers on operator choices and application QoE tuning. We released the datasets and artifacts at https://github.com/SIGCOMM24-5GinMidBands/artifacts.

CCS CONCEPTS

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

KEYWORDS

5G, 5G Mid-Band, 5G mmWave, Mid-band vs. mmWave, PHY Layer, Measurement, Latency, Video Streaming, Performance, QoE, Dataset

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1 INTRODUCTION

The widespread commercial deployment of the Fifth Generation (5G) networks is a reality today. Unlike its predecessors, the 3rd Generation Partnership Project (3GPP) has specified that 5G New Radio (NR) operates across different radio bands for radio access [7]: *i.e.,* Frequency Range 1 (FR1) which includes low-bands (below 1 GHz) and mid-bands (1 to 6 GHz), and Frequency Range 2 (FR2) with high-bands at millimeter-wave (mmWave) frequencies (above 24 GHz). Despite its wider bandwidth and early deployment since May 2019 [30], mmWave 5G has faced numerous challenges due to its limited coverage range, sensitivity to obstructions, erratic throughput, and other deployment complexities [14, 21, 55, 57]. With minimal unused spectrum remaining in the low-bands, mid-bands have emerged as the favored choice for global 5G deployments [29]. According to a report by GSMA (Global System for Mobile Communications Association) Intelligence [38], as of January 2023, only 7% of 5G deployments worldwide are in FR2, with the majority situated in mid-bands. While a small fraction of 5G deployments exists in high-bands, mmWave 5G characterization has received relatively more attention [27, 31, 36, 51, 57–60, 67, 68] than mid-bands 5G in terms of performance [28, 46, 63, 66, 76].

The breadth of characterization regarding mid-band 5G is currently lacking for two main reasons. *First*, compared to mmWave 5G, mid-band has seemingly lower technical innovations at the physical layer (PHY). Nevertheless, as we will show in this paper, mid-band 5G is capable of achieving peak downlink throughput beyond 1 Gbps (§4); while this is significantly lower than the peak downlink throughput attainable by mmWave 5G (which can be up to 4 Gbps), mid-band 5G channel variability is far lower than that of mmWave 5G, especially under mobility (§7). This is instrumental to applications such as video streaming (§6). *Second*, worldwide, the roll-out of 5G deployments in mid-bands are considerably diverse. In the U.S., the deployment of 5G in mid-bands has been slower compared to the rest of the world [14], primarily due to difficulties in acquiring mid-band spectrum. Whereas, in the rest of the world the uptake of 5G in mid-bands has been faster than in mmWave. The geographically diverse and unbalanced nature of mid-band 5G deployments make conducting comprehensive large-scale comparative studies challenging, *yet much needed.*

To gain a better understanding on 5G performance in mid-bands, we conduct – to the best of our knowledge – the first *cross-continental* 5G measurement campaign in the U.S. and four European countries (France, Germany, Italy and Spain). The goal of our study is multifold. *First, we aim to provide a comparative analysis of mid-band 5G performance in the U.S. and Europe.* We choose these geographical locations as representative examples of a large unified market (i.e., the U.S.) and a fragmented one (i.e., Europe), where multiple national and cross-national carriers[1] operate in the market, with each of them typically owning and managing network infrastructure *independently* within their respective European countries. Previous measurement studies in multiple European countries focused either on 4G [53, 54] or 5G technology from the perspective of the mobile network operator [63], and for the case of international roaming, where users access voice and data services abroad on a network different from their home provider. In contrast, our paper studies user-centric 5G performance when users access their home network operator in different countries. We report insights about the user-centric roaming experience in 5G mid-bands in a separate study [42]. *Second, we aim to characterize mid-band 5G performance across operators and countries and investigate how deployment settings, configurations and physical layer (PHY) parameters affect user-perceived 5G performance.* These in-depth analyses are made possible through the use of a professional 5G measurement tool that collects detailed 5G lower-layer information at the slot-level (the finest time scale possible) and carefully designed measurement methodology and experiments (§2). *Last but not least, we aim to quantify the impacts of 5G PHY performance on application quality-of-experience (QoE) by dissecting data across the layers.* To this end, we focus on video streaming, a predominant application that consumes a large majority of mobile data.

Contributions. Our study is grounded on datasets comprising 5600+ minutes of 5G network measurements. These datasets, which exceed 5 TB of data, consist of Key Performance Indicators (KPIs) and signaling messages collected from seven major worldwide operators across Europe and the U.S. Through carefully designed measurements and in-depth data analytics, we carry out a *cross-country* and *cross-continent* comparative analysis of 5G mid-band performance by extracting and dissecting detailed 5G network configurations, PHY parameters and other deployment settings. Our key findings are summarized below.

• Our study reveals the diversity in 5G mid-band deployments within and across Europe and the U.S. in terms of mid-band channels, channel bandwidth and other PHY configurations (§3). For example, all European operators use n78 band, with channel bandwidth ranging from 80 MHz to 100 MHz. Whereas, both AT&T and Verizon deploy their 5G mid-band services using C-band while T-Mobile rely on the lower range of the 5G mid-band spectrum. Due to more fragmented mid-band spectrum in the U.S., the channel bandwidth of 5G mid-band channels is generally smaller than those of their European counterparts. Hence, U.S. operators resort to carrier aggregation (CA) to boost the overall bandwidth, while the European operators have yet to deploy CA.

• While channel bandwidth is important (as it determines the maximum resource blocks/elements (RBs/REs) available to users), other parameters such as MCS (modulation and coding scheme) and MIMO layers can play a more critical role in determining user-perceived 5G downlink (DL) throughput performance, especially when channel bandwidth is similar (§4). For example, we observe that with a 90 MHz 5G mid-band channel, Vodafone Spain consistently outperforms Orange Spain which has a 100 MHz channel. This performance gap can be attributed to dynamic configuration of parameters such as MCS and MIMO layers which hinge more critically on channel conditions. Hence other deployment settings such as coverage also matter. CA employed by U.S. operators significantly boosts 5G mid-band throughput beyond 1 Gbps.

• In the NSA (non-stand-alone) deployments used by most European and U.S. operators, uplink (UL) transmissions use both 5G and 4G channels (§4.2). This makes characterizing and comparing 5G UL throughput performance more difficult and less meaningful. In terms of the 5G mid-band user plane latency performance (§4.3), channel bandwidth has no bearing; instead it is directly influenced by factors such as BLERs (block-level error rates) and TDD (Time Division Duplexing) frame structure.

• While it is known that aggregate statistics such as average throughput or throughput distribution cannot adequately characterize channel performance, this is particularly true in 5G networks because the interplay between different parameters increases performance variability with respect to previous generations; capturing *channel variability* is thus important (§5). We introduce *scaled variability* metrics to quantify 5G throughput and parameter variability across multiple time scales. 5G throughput variability is strongly influenced by 5G parameter variability. Their variability can span a large range from milliseconds (ms) to several seconds (s). We also investigate channel variability across locations and number of active users, with expected results.

• Using video streaming as a case study, we quantify the impacts of 5G PHY performance on application QoE (§6). By dissecting 5G PHY parameters and cross-correlating them with the application decision events generated by the ABR (adaptive bit rate) algorithm, we demonstrate how 5G PHY throughput and channel variability directly contribute to application QoE metrics such as average bit rates and stall times. We show that by simply reducing the video chunk length so as to allow the ABR algorithm to make decisions at a faster time scale, we can improve the average bit rates by up to 40% and reduce the stall time percentage by up to 50%.

• Lastly, we quantitatively compare 5G mid-band performance with 5G mmWave performance under mobility to illustrate why 5G mid-band is viewed as the "sweet spot" for 5G deployments (§7).

Dataset and Artifact Release. To support future research, we make our dataset, artifacts, source code, processing scripts, plots and results publicly available through our website: https://github.com/SIGCOMM24-5GinMidBands/artifacts

Lessons Learned and Implications. Our study shows that characterizing 5G performance can be fairly complex and requires accounting for diverse parameters, and their intricate interplay. It sheds light on many aspects of 5G deployments and performance. It also provides valuable lessons to network vendors, mobile operators and application developers. Instead of focusing on boosting peak performance, it is crucial for network operators to ensure performance consistency and stability in large deployments. Hence factors such as coverage, density and mechanisms for reducing channel variability also become important. 5G operators should take a holistic approach when planning or upgrading 5G deployments. From the application perspective, developing adaptive algorithms that can better accommodate 5G channel variability – making them 5G-network-aware – is key to enhance application QoE.

[1] Throughout the paper, we use the terms "carrier," "operator," and "mobile network operator" interchangeably.

Ethical Considerations. This study was carried out by the research team, volunteers, and paid graduate students. No personally identifiable information (PII) was collected or used, nor were any human subjects involved. We purchased several experiment-only smartphones and contract cellular data plans in each country for our experiments. Our study complies with the customer agreements of all 5G operators. This work does not raise any ethical issues.

2 MEASUREMENT CAMPAIGN

Locations and 5G Operators. Our study focuses on 5G mid-bands. At the time of our study, multiple 5G bands are available in the U.S., including mmWave, mid-band and low-band [60]. By contrast, European carriers have deployed 5G only in mid and low-bands. To ensure a fair comparison evaluation, we conduct measurements in specific cities where mid-band is available: Madrid in Spain, Paris in France, Munich in Germany, Rome in Italy, and Chicago in the United States. We have chosen operators that hold the lion's share of the mobile market in these countries [23, 74]. In Europe, we study Orange and Vodafone in Spain, Orange and Société française du radio téléphone (SFR) in France, Vodafone in Italy, and Deutsche Telekom and Vodafone in Germany. In the U.S., we study AT&T, T-Mobile, and Verizon. In each chosen city and for every operator, we leveraged various resources, including related works [18, 28, 32, 58, 60], and platforms like Ookla Speedtest [6] and nperf [61], to pinpoint a minimum of two areas in well-frequented tourist areas with 5G mid-band coverage for our measurements.

Measurement Platforms and Testbed. Conducting measurement studies in the wild is known to be very challenging and can lead to several inconsistencies, especially across countries. Therefore, to maintain consistency across countries and ensure reliable data quality as best as possible, we create a measurement testbed comprising numerous back-end servers and several tools, along with a diverse set of customized scripts designed for experiment automation and data collection. We use Ookla Speedtest servers and leveraged Amazon's partnership with Verizon in the U.S. and Vodafone in Germany [2] to deploy edge servers, which are located within the 5G operator network in the same city as the UE (User Equipment). Unlike other alternatives like M-lab [33], Ookla speedtest servers are, if not within the cellular core network, the closest edge servers to the cellular core network, which makes them ideal to measure latency without the need to correct additional latency components. We further leverage cloud servers offered by three leading global cloud service providers: Amazon AWS Cloud [1], Microsoft Azure Cloud [16], and Google Cloud Platform (GCP) [34]. Due to the relatively small land area size of each European country compared to the U.S., cloud service providers may not have cloud facilities in each city or even have a presence in every country. Therefore, we use GCP to deploy servers located in Spain and Italy, Azure Cloud for servers located in France, and AWS (both Local Zone and Wavelength) for servers in Germany and the U.S.

5G UEs and Other Measurement Tools. We use a consistent set of six Samsung Galaxy S21 Ultra (S21U) flagship smartphones across all operators in each country. For data collection, we utilized a professional tool Accuver XCAL [5] with custom scripts. XCAL allowed us to gather comprehensive 5G NR control plane and user/-data plane information directly from the chipset. It operates on a laptop connected to smartphones via USB or USB-C, enabling data collection at various NR RAN (Radio Access Networks) protocol stack layers, ranging from the physical (PHY) layer to the Radio Resource Control (RRC) layer. We also used GNetTrack Pro [15] app to identify "strong" 5G mid-band coverage easily.

Table 1: Statistics of the data collected across countries.

Country	Spain	France	Italy	Germany	USA
City	Madrid	Paris	Rome	Munich	Chicago
Operators	Orange Vodafone	Orange SFR	Vodafone	Telekom Vodafone	T-Mobile Verizon AT&T
# Unique SIM cards	23				
# Smartphone (# Models)	6 (3)				
# Servers Used	122				
Data consumed on 5G	5.02 Terabytes				
5G Network Tests	5600+ minutes				
Duration	17 Weeks				

Profiled Applications. To assess the impact of 5G parameters on application QoE, we designed and conducted a series of live test over 5G, including; *(i)* bulk data transfer using iPerf3 [39] and *(ii)* video streaming. We also conducted file downloads, roaming, and traceroute experiments, the results for which are reported in [42].

Data Collection. Using the above measurement platform, we have carried out a *cross-continent*, *cross-country* measurement campaign. Our systematic approach to conducting experiments in each country consists of the following five aspects. ❶ *Scouting for 5G Coverage:* We rely on GNetTrack Pro to scout 5G coverage and identify locations with Reference Signal Received Power and Quality (RSRP & RSRQ) values greater than −90 dBm and −12 dB respectively, *i.e.,* areas with "good" signal quality [45]. ❷ *Data Collection:* We collected detailed 5G mid-band data for approximately 10 consecutive days in each country. ❸ *Experimental Sessions:* Within a day, we conducted experiments for an average of seven hours, spanning different time periods, including mornings, rush hours, and nighttime. ❹ *Mitigating Potential Issues:* To ensure reliable data quality, we use all contract SIM cards to avoid our throughput from being throttled by network operators. We also minimize UE-related factors like turning off the phones' Wi-Fi interface, closing/stopping all running apps, disabling background app refresh, placing the phones on flat surfaces during stationary experiments, and attaching them to car phone holders during driving experiments. ❺ *RRC State Control:* The promotion time from RRC idle state to RRC connected state introduces delay. This factor should be excluded during the measurements, and for this, we use the same methodology [27], *i.e.,* before executing each experiment, we play a random video for 20 seconds, close the application, and wait for 5 seconds before starting our measurement.

To summarize, we conducted 5600+ minutes of measurements of 5G mid-band services offered by seven mobile operators in selected cities in Spain, France, Italy, Germany, and the U.S. over a period of 4.5 months. Table 1 summarizes the key statistics our dataset.

3 5G MID-BAND CONFIGURATIONS

This section offers a detailed synopsis of 5G in mid-bands in both Europe and the U.S. We provide a comparative discussion of key configuration parameters (hereafter referred to as config(s)) employed by each operator under analysis and set the stage for our forthcoming analysis in §4 by presenting the theoretical maximum

Table 2: EU Network configs

Country	Spain			France		Italy	Germany	
Operators	Orange		Vodafone	Orange	SFR	Vodafone	Telekom	Vodafone
Acronym	O_Sp		V_Sp	O_Fr	S_Fr	V_It	T_Ge	V_Ge
SCS (kHz)	30							
Duplexing Mode	TDD							
5G NR Band	n78							
ChannelBandwidth (MHz)	100	90	90	90	80	80	90	80
Max. Bandwidth (N_{RBs})	273	245	245	245	217	217	245	217
Carrier Aggregation	No							

Table 3: U.S. Network configs

	U.S.			
Operators	T-Mobile		Verizon	AT&T
Acronym	Tmb_US		Vzw_US	Att_US
SCS (kHz)	15	30		
Duplexing Mode	FDD	TDD		
5G NR Band	n25	n41	n77 (C-band)	n77 (C-band)
ChannelBandwidth (MHz)	20+5	100+40	60	40
Max. Bandwidth (N_{RBs})	51 + 11	273 + 106	162	106
Carrier Aggregation	Mid + Mid-Band		Mid + Low-Band	Mid + Mid-Band

PHY throughput defined by 3GPP. This formula effectively brings together the significance of prominent 5G configuration parameters we will discuss thereby highlighting the importance of profiling network configurations.

3.1 A Comparative Study in U.S. and Europe

Table 2 summarizes the key 5G channel config parameters relevant to our research for all European operators under study. Whereas Table 3 summarizes the same set of parameters for the U.S. operators. We detail the process for parameter extraction in Appendix 10.1.

5G Mid-Band Channels and Channel Bandwidths. In Europe, 5G mid-band usage and deployment is more uniform. All operators utilize the n78 band, characterized by a spectrum range spanning from 3300 to 3800 MHz. This specific band is a sub-segment of n77 (3300 – 4200 MHz), commonly referred to as the C-Band [75]. As per 3GPP specifications [11], channels in the n78 band multiplex DL and UL data within the same frequency in TDD. Differences emerge in the channel bandwidth adopted by each operator within each country, spanning from 80 MHz, 90 MHz, to 100 MHz.

An equivalent examination of U.S. operators' bands and channel bandwidth reveals a more diverse deployment when compared to their European counterparts. Officially, both AT&T and Verizon opt for the deployment of their 5G mid-band networks within the C-band. The channels allocated by both AT&T and Verizon fall within the upper spectrum range of the n78 band, aligning with the European usage. Specifically, Verizon employs a channel bandwidth of 60 MHz, while AT&T opts for a narrower 40 MHz bandwidth[2]. In stark contrast, T-Mobile adopts a more diverse approach by deploying its 5G mid-band services across two distinct bands: n41 and n25. Within the n41 band (2.5 GHz, 2496 – 2690 MHz), T-Mobile leverages two channels, one with a bandwidth of 100 MHz and another with 40 MHz, both configured for TDD operation. In the n25 band (1.9 GHz, 1850 – 1915 MHz), T-Mobile utilizes two (pairs of) channels, each with a bandwidth of 20 MHz and 5 MHz, respectively. The n25 band operates under the Frequency Division Duplexing (FDD) mode, accommodating different DL and UL channels on the same frequency band interleaved by a guard band between DL and UL. T-Mobile effectively combines these n41 and n25 channels in various permutations for carrier aggregation, as we elaborate below.

Except for the T-Mobile n25 FDD channels, all examined European and U.S. 5G mid-band channels operate using 30 kHz as SCS [8]. The channel bandwidth and SCS (Sub-Carrier Spacing) together determine the *maximum transmission bandwidth* for the channel, which is quantified in terms of *resource blocks* (RBs - N_{RB}). A resource block is the basic unit of radio resource allocation in the frequency domain used by 5G base stations (gNBs). The equivalence in both the frequency and time domain is *resource elements* (REs).

For TDD channels, another key 5G config parameters is the *TDD Frame Structure*, which exerts a significant influence on various aspects of the network, including bandwidth for DL and UL channels, BLERs and MCS adaptation. Due to its technical intricacies, we delegate the discussion of TDD frame structure and its implications on 5G performance to future works.

MCS and CQI-MCS Mapping. During transmissions, a 5G gNB also dynamically signal to the UE, a set of parameters (typically on a *per-slot* basis or (semi-)periodically within 10's ms time scales). These dynamic parameters are sent as part of the DCI (downlink control information) and play a critical role in 5G performance, as will be shown later. They include, among others, specific RBs/REs allocated, the modulation order (QPSK, 16QAM, 64QAM and 256QAM) and code rate (represented by the MCS index). We refer the reader to Fig. 21 in Appendix 10.2 for more details on the procedure. The MCS index is typically chosen based on the channel quality indicator (CQI) periodically fed back by the UE and may be further adapted based on other sounding reference signals. CQI has a range of [1,15], with 15 indicating the best channel condition.

The mapping from CQI to MCS is determined by the DCI format used in each slot. DCI format 1_1 indicates to the UE to use 256QAM as modulation order, whereas DCI format 1_0 (used, *e.g.,* when the channel conditions worsen [41]) indicates the use of the 64QAM[3]. The data transmitted in a slot is referred to as a *transport block* (TB). Given N_{RB} (and REs per slot) allocated, the size (in Bytes) of a TB is determined by the MCS [see section §6.1.1.1 in 3GPP TS38.214 [9]]. Thus, given the same number of RBs allocated to the UE, a high MCS index produces a larger TB size, translating into high throughput. While the (two) MCS index tables are standardized, 3GPP leaves the CQI-MCS mapping to vendor implementation (in other words, for a given CQI value, different vendors may map it to different MCS indices).

MIMO and Carrier Aggregation (CA). To increase throughput, all operators under study deploy (up to) 4×4 Single-User MIMO. However, the effective number of MIMO layers configured during transmission largely varies across operators. In terms of CA, all three U.S. operators employ CA with mid-band (and low-band)

[2] It is reported [35] that AT&T has deployed another 3.45 GHz 5G mid-band channel of 40 MHz in Phoenix, U.S. However, this channel has not yet been deployed in the cities we have conducted our measurements.

[3] Several 5G mid-band operators use 256QAM as the maximum modulation order while a few use 64QAM as the maximum modulation order.

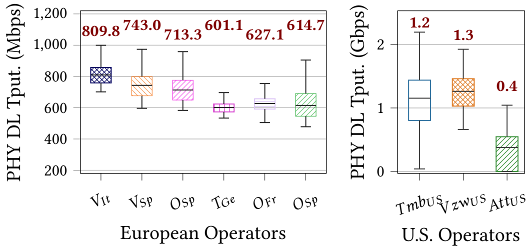

Figure 1: DL Tput. of European Operators: Vodafone Italy (V_{It}); Vodafone Spain (V_{Sp}); Orange Spain (O_{Sp}); Deutsche Telekom (T_{Ge}), and Orange France (O_{Fr}) and U.S. Operators: T-mobile (Tmb_{us}), Verizon (Vzw_{us}), and AT&T (Att_{us}).

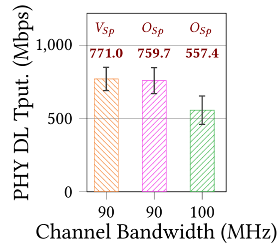

Figure 2: DL Tput. with CQI≥12 for Vodafone & Orange Spain with 90 MHz, and Orange Spain with 100 MHz].

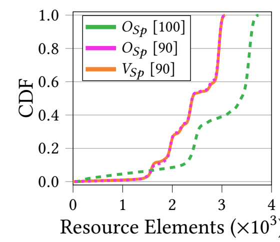

Figure 3: REs allocations for Vodafone & Orange Spain with 90 MHz, and Orange Spain with 100 MHz].

channels[4]. This is partially due to the fact that the mid-band spectrum is more fragmented in the U.S. The operators resort to CA to form aggregate channels of 100 MHz and beyond. For example, we have observed that T-Mobile aggregates up to four channels to form an aggregate channel of 180 MHz. Table 3 shows a few example channel combinations. In contrast, none of the European operators have yet deployed CA; thus, their maximum channel bandwidth is up to 100 MHz only.

Non-Stand-Alone (NSA) vs. Stand-Alone (SA). At the time of our measurement studies, all European operators, as well as AT&T and Verizon in the U.S. have implemented their 5G mid-band services exclusively in the NSA mode. However, T-Mobile in the U.S. has deployed both NSA and SA mid-band 5G services. Therefore, to ensure a fair comparison, we focus exclusively on T-Mobile NSA deployment. Similar to [31], we observe that all operators predominantly utilize the 5G NR channel for DL transmissions. In contrast, most operators in both Europe and the U.S. opt to combine both 5G NR and 4G LTE (and in some cases, use 4G LTE only) for UL transmissions as we discuss further later in § 4.2.

3.2 Characterizing Mid-Band Throughput

To highlight the significance of the aforementioned config parameters in influencing user-perceived performance, we use the 3GPP 5G NR expression to compute the attainable PHY throughput [4] in Mbps. This formula effectively correlates and quantifies the theoretical *maximum* PHY throughput, establishing a connection with the previously discussed configuration parameters.

$$Max\_Throughput\ (in\ Mbps) =$$
$$10^{-6} \cdot \sum_{j=1}^{J} \left\{ v_{layers}^{(j)} \cdot Q_{MCS}^{(j)} \cdot f^{(j)} \cdot R^{(max)} \cdot \frac{12 N_{RB}^{BW(j),\mu}}{T_s^{\mu}} \cdot (1 - OH^{(j)}) \right\},$$

where J is the number of carriers component during CA; for each carrier component j, $v_{layers}^{(j)}$ is the number of MIMO layers used; $Q_{MCS}^{(j)}$ is the maximum modulation order (*e.g.,* 6 for 64 QAM and 8 for 256 QAM); μ depends on the SCS; $T_s^{\mu} = 10^{-3}/14 \cdot 2^{\mu}$ is the average OFDM symbol duration in a slot of SCS with μ; $N_{RB}^{BW(j),\mu}$ is the maximum RB allocation for a channel with bandwidth $BW(j)$ for SCS μ; $f^{(j)}$ is the scaling factor and may take values 1, 0.8, 0.75, and 0.4, depending on the MIMO layers and maximum modulation order used by each carrier component, and R_{max} is the code rate. The formula applies to both DL and UL transmissions, where $OH^{(j)}$ is the overhead value depending on DL/UL and the frequency range of the channel. For all 5G mid-bands with SCS fixed to 30 kHz, $\mu = 1$; for DL, $OH^{(j)} = 0.14$, and for UL, $OH^{(j)} = 0.08$. When no CA is used (*i.e.,* $J = 1$), $f^{(j)} = 1$. The number of RBs allocated per slot is bounded by N_{RB} (row 7 in Tables 2 and 3), namely, $N_{RB}^{BW(j),\mu} \leq N_{RB}$. Using our dataset, we compute the theoretical achievable PHY DL throughput and compare with the maximum observed throughput. For example, equation 3.2 yields a maximum PHY DL throughout of 1213.44 Mbps (at 90 MHz channel bandwdith) and 1352.12 Mbps (at 100 MHz), which are about 14% and 29% higher than the DL perceived throughput in our study for Vodafone Spain and Orange Spain respectively.

Takeaways §3. The current landscape of commercial 5G mid-band deployment shows significant variability in configurations. The same operator may use different network settings in different countries. We analyze the impact of these on the PHY network performance next in §4.

4 5G MID-BAND PHY PERFORMANCE

We present measurement results on 5G PHY (physical layer) performance from the DL/UL throughput and latency perspectives. We also dissect the effects of 5G config parameters (such as channel bandwidth, RB allocation, MCS, MIMO layers and CA) on 5G mid-band performance.

4.1 PHY DL Throughput Performance

We start with 5G mid-band DL throughput performance analysis and comparison. The results are shown Figure 1 for both (a) the European operators and (b) the U.S. operators. While theory suggests that wider channel bandwidth should result in higher measured throughput, our empirical findings tell a different story. Using Spain as a case study, Figure 2 shows the PHY layer DL throughput of Vodafone Spain (V_{Sp}) with 90 MHz channel bandwidth and the two Orange Spain channels of 90 and 100 MHz (*i.e.,* O_{Sp}). Under good channel conditions (CQI ≥ 12), O_{Sp} with 100 MHz exhibits the lowest average DL throughput of 557.4 Mbps. In contrast, O_{Sp} and V_{Sp}, both with a 90 MHz channel, achieve an average DL throughput of 759.7 Mbps and 771.0 Mbps, respectively, an increase of about 37%. To demystify this large performance difference, we dive into

[4]Currently CA is used only for DL transmission. However, both T-Mobile and AT&T are actively exploring CA for UL transmissions [13, 73] to increase the overall UL throughput (see § 4.2)

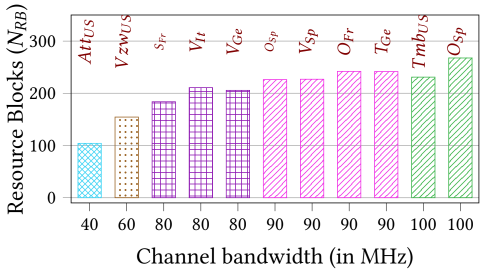

Figure 4: Maximum number of RBs allocated by each operator.

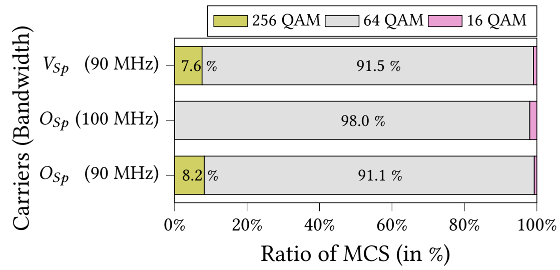

Figure 5: Mode Scheme utilization percentages for operators in Spain.

the lower-layer 5G PHY parameters to dissect their impacts on the measured 5G PHY DL throughput (as seen by the UE).

Impact of Radio Resource Allocation. We first examine the number of RBs/REs allocated to the UE during the DL throughput measurements using iPerf. Figure 3 shows the cumulative distribution of the REs allocated to the UE during those experiments. We see that O_{Sp} (100 MHz) tend to allocate more REs to the UE (as it has more configured RBs due to its wider channel bandwidth) than both O_{Sp} (90 MHz) and V_{Sp} (90 MHz). Hence the radio resource allocation does not contribute to the performance difference (which would have led to the opposite effect). This also (indirectly) rules out the possibility that other users that might be active at the same time of our measurements – thus competing for the radio resources – are the cause for the observed lower DL throughput of O_{Sp} (100 MHz). In fact, we find that during iPerf DL throughput measurements, all operators in our study tend to allocate close to the "maximum" RBs (and REs) to the UE as shown in Figure 4.

Impact of Mode Scheme Configured and MCS. We next examine the maximum modulation order configured by the three operators. We find that O_{Sp} (100 MHz) uses QAM64 as the maximum modulation order whereas both O_{Sp} (90 MHz) and V_{Sp} (90 MHz) use QAM256. As the QAM256 modulation order allows high coding rates which yield higher spectrum efficiency, this is clearly an important contributing factor to the overall higher DL throughput performance of O_{Sp} and V_{Sp} over O_{Sp} (90 MHz). But this factor alone cannot explain the 37% performance difference we have observed. This claim is supported by the results in Figure 5, where we use the MCS indices signaled by the gNB to extract the *actual* modulation orders being used during the DL transmissions. We see that the highest modulation order (*i.e.,* QAM256) is only used about 7.6% and 8.2% by V_{Sp} (90 MHz) and O_{Sp} (90 MHz). In all three cases, the majority of the modulation order used is QAM64, 91.5% for V_{Sp} (90 MHz), 98.9 % O_{Sp} (100 MHz) and 91.1 % O_{Sp} (90 MHz).

Impact of MIMO Layers. Lastly, we consider the MIMO layers. Figure 6 shows the percentage of times that 1, 2, 3 and 4 layers were used by each operator during the experiments. We see that in the case of V_{Sp} (90 MHz) and O_{Sp} (90 MHz), 4 layers (i.e., 4×4 MIMO) are used 87.1% and 83.8% percent of times, respectively; whereas in the case of O_{Sp} (100 MHz), they are only used in less than 14% percent of the times; for the majority of times (74.1%), 3 layers are used. Compared with only 1 layer (i.e., no MIMO), 4 MIMO layers essentially quadruples the radio resources allocated to the UE and thus increases the (theoretical) data rates by 4-fold, see eq.3.2 in §3.2. The number of MIMO layers used is thus a major contributing factor to the observed DL performance differences.

This now raises the question why V_{Sp} (90 MHz) and O_{Sp} (90 MHz) are able to use higher numbers of MIMO layers more often than O_{Sp} (100 MHz). As the decision made by the base station regarding the number of MIMO layers to use hinges critically on the channel conditions experienced by the UE, answering this question requires us to examine other factors related to 5G deployment settings such as the locales, coverage and density of base stations and the surrounding environments, and so forth. As a case study, we use V_{Sp} (90 MHz) and O_{Sp} (100 MHz) to illustrate. Figure 7 shows the RSRQ (reference signal received quality) values reported by the UE when it is connected to either V_{Sp} (90 MHz) or O_{Sp} (100 MHz). Here we walk along the same route. We see that the UE experiences significantly better signal strength when connected to V_{Sp} (90 MHz) than when connected to O_{Sp} (100 MHz). This explains why 4 MIMO layers are used more often by V_{Sp} (90 MHz). The difference in RSRQ values can be attributed to the fact that V_{Sp} (90 MHz) deploys three 5G base stations, thus providing better coverage density, whereas O_{Sp} (100 MHz) deploys only two 5G base stations in the same area (see Figure 22 in the Appendix 10.3.)

Figure 8 summarizes the key 5G parameters that affect 5G DL throughput and their interplay. While in the above we use the mobile operators in Spain to illustrate the effects of 5G configurations

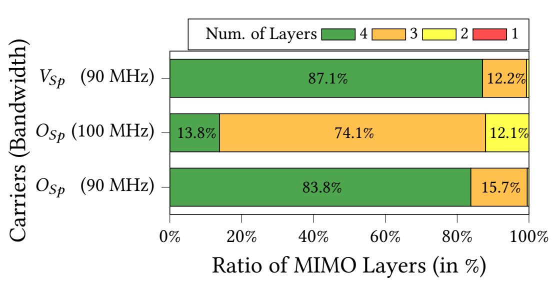

Figure 6: MIMO Layers Utilization for Spanish Operators.

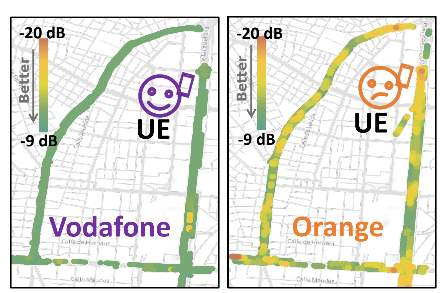

Figure 7: RSRQ on a map for V_{Sp} 90 MHz and O_{Sp} 100 MHz.

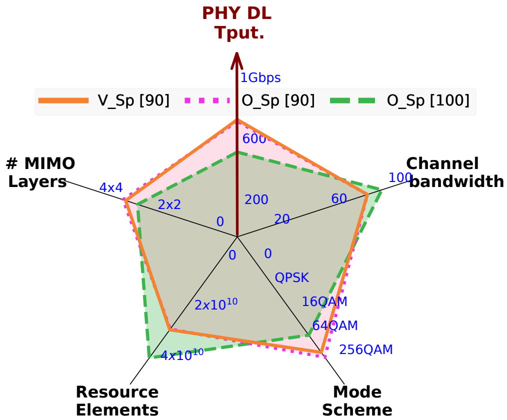

Figure 8: Spider plot shows the factors which affect Physical (PHY) layer downlink throughput and their interplay with each other.

and parameters on observed 5G DL throughput performance differences. The same analysis is also applicable to other operators in Europe as well as in the U.S. For completeness, we also investigate the impact of CA on 5G DL throughput [78]; see Appendix 10.3 for some representative results.

4.2 PHY UL Throughput Performance

Figure 9 shows the UL throughput performance of the European operators and Figure 10 shows for the three U.S. operators under "good" channel conditions (*i.e.,* CQI ≥ 12). We see that for all the operators, the PHY UL performance is significantly lower than that of the PHY DL performance, all well below 120 Mbps. This is due to the TDD frame structures used in current 5G mid-band deployments, where far fewer slots (and symbols per the "flexible" slot) are allocated for UL transmissions than DL transmissions, creating this *DL-UL performance asymmetry.*

In addition, the channel bandwidth appears to have little correlation with the observed UL throughput performance. For example, despite having a channel of 100 MHz, T-Mobile yields the worst performance. An in-depth analysis shows that T-Mobile prefers to utilize the LTE connection rather than the 5G NR connection for UL transmission. The fourth box plot (denoted by LTE_US) in Figure 10 shows the corresponding UL throughput performance of the 4G LTE channel that is used at the same time with the 100 MHz 5G channels for UL transmissions. In fact, the same observations also apply to other U.S. operators (see also [31]) and European operators. This is because in the non-stand-alone (NSA) mode, UL transmissions rely on both 5G and 4G channels (*dual-connectivity*) to attain

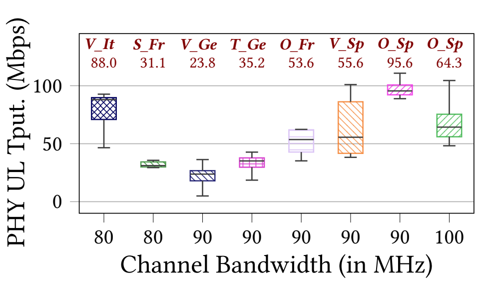

Figure 9: [Europe] PHY UL Throughput with CQI ≥ 12.

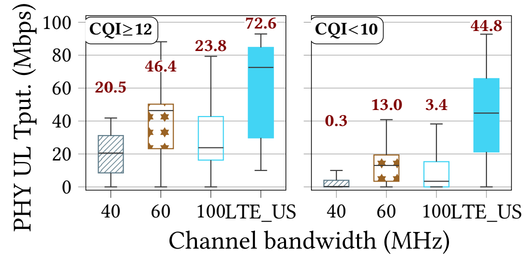

Figure 10: [U.S.] PHY layer UL throughput

higher throughput, and sometimes exclusively use 4G channels due to their generally larger coverage and better channel quality. As such, this makes characterizing and comparing 5G UL throughput performance more challenging, and relying on the UL throughput performance of 5G channels alone for performance comparison becomes less meaningful.

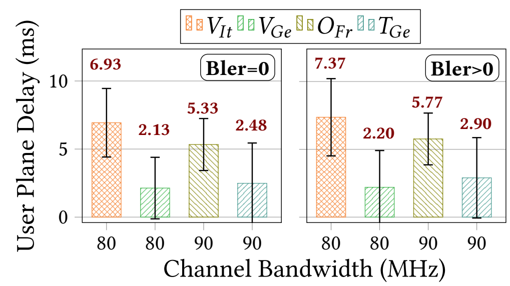

Figure 11: 5G PHY user plane latency.

4.3 PHY Latency Performance

Finally, we compare the observed 5G mid-band PHY *data (user) plane latency* of the various European and U.S. operators. Inspired by [24, 27], we define the user plane delay as *PHY DL plus UL latency.* Figure 11 shows the measured PHY data plane latency results for four representative operators in Europe for two cases: *(i)* BLER = 0 (*i.e.,* no bit errors, thus no retransmissions), representing the best case scenario; and *(ii)* BLER > 0 where at least one PHY retransmission is performed, thus increasing the PHY user plane latency. We observe that the channel bandwidth has no bearing on the observed PHY user plane latency. For example, both with 80 MHz and BLER = 0, Vodafone Italy (V_{It}) has the worst latency (6.93 ms), while Vodafone Germany (V_{Ge}) has the best latency (2.13 ms). Not surprisingly, with more retransmissions (higher BLERs), latency increases. This performance difference is in fact due to the different TDD frame structures used by the two operators [27]. We find that V_{It} uses DDDDDDDSUU while V_{Ge} deploys the DDDSU.

Takeaways §4. We find disparities in the attainable DL throughput and pinpoint the root cause not to the channel bandwidth or resource utilization (RBs), but to MCS and MIMO layers configurations. UL throughput and latency are coupled to the TDD frame structure configured. As radio resources are usually fully utilized in mid-bands, further performance optimization gains can only come by better adapting to channel propagation characteristics. We analyze in §5 variability over time of the aggregate statistics observed so far.

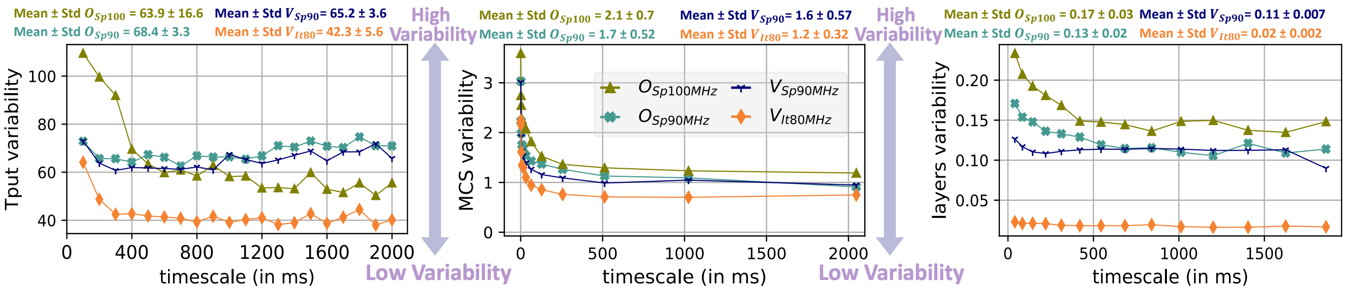

Figure 12: Variability of 5G Throughput, MCS and MIMO parameters across different time scale: O_{Sp}, V_{Sp}, and V_{It} [2 seconds]

5 5G MID-BAND CHANNEL VARIABILITY

So far, we have analyzed 5G mid-band performance across multiple operators and countries and investigated how 5G config parameters such as channel bandwidth, RB allocation, MCS, and number of MIMO layers affect the measured performance. In particular, we have shown that when the configured bandwidth of 5G mid-band channels is similar, channel conditions – as measured by (the percentages or distributions of) MIMO layers and MCS values – determine the observed (average) throughput by the UE over time. To formally quantify 5G channel dynamics, we utilize *(scaled) variability* metrics defined as follows.

Scaled Variability Metrics. Let $x_1, ..., x_n$ be a sequence of data points sampled at the finest time granularity τ. (In our case, it is at the slot-level, *i.e.,* $\tau = 0.5$ ms. Also, without loss of generality, we assume n is a multiple of 2's powers.) Hence, the total time duration of the measurement period is $T = N\tau$. For a given time scale t, where t is a multiple of τ, say $t = 2^k\tau$ for some $k \geq 1$. We define $V(t)$, *variability at time scale t* (of the sampled data point sequence), as follows:

$$V(t) := \frac{1}{m-1}\sum_{j=1}^{m-1} |\bar{X}_{j+1} - \bar{X}_j| \quad (1)$$

where $m = T/t$ and $\bar{X}_j$ is the average of x_i's that fall within the i time interval of length t. For example, for $t = 2^k\tau$, $\bar{X}_j = \frac{1}{2^k}\sum_{h=(j-1)\cdot 2^k}^{j\cdot 2^k - 1} x_h$, $j = 1, .., m$.

The sum in equation 1 measures *cumulatively* how the sequence of data points vary from one time interval of length t to the next. $V(t)$ thus quantifies the (average) variation[5] at time scale t. Clearly, the larger $V(t)$ is, the more varied the data point sequence is at time scale t. By varying t, we can measure variability across different time scales. We can also segment a long sequence into multiple sub-sequences, and quantify the variability of the sub-sequences.

5.1 5G PHY Tput and Parameter Variability

We apply scaled variability metrics to quantify 5G channel dynamics. We use data from four European operators (V_{It}, V_{Sp}, O_{Sp} with 90, and O_{Sp} with 100 MHz 5G mid-band channels) for the analysis. Figure 12 portrays the variability of measured 5G throughput (Tput) [left plot] as well as the variability of two key 5G parameters, MCS values [middle], and MIMO layers [right], across various time scales from 0.5 ms up to 2 secs. The choice for 2 secs is motivated by the fact that we observe that throughput stabilizes at around 400 ms as Figure 12 indicates. Hence, we used a maximum observation window 5× larger for completeness. We also annotate the plots with the average values (± std dev.). We see that all four channels exhibit much higher variability at smaller time scales (below 100 ms), which decreases as the time scale increases. Beyond certain time scales (around 0.2 s to 0.5 s), variability tends to "stabilize", indicating that the channel conditions appear to oscillate around these time scales.

Figure 12 shows that the 5G throughput observed with V_{It} 80 MHz yields the highest average throughput, corresponding to the lowest variability for the MCS values and MIMO layers over all time scales. In contrast, the 5G throughput observed from O_{Sp} 100 MHz is the lowest and it exhibits the highest variability over all time scales. This is because the channel conditions varied frequently triggering numerous re-configurations of MCS values and MIMO layers used, resulting in an overall lower (average) throughput (even though it has the widest channel bandwidth).

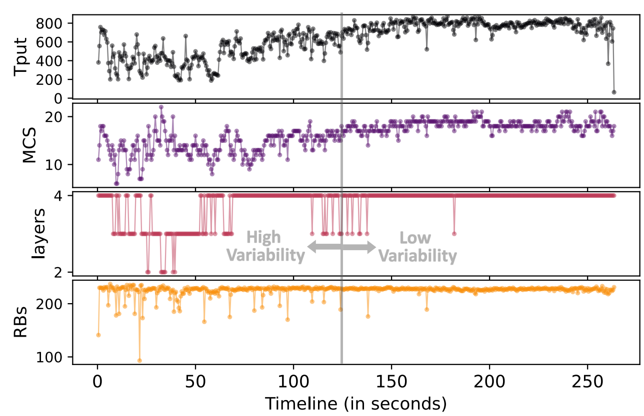

Figure 13: Impact of 5G parameter variability on 5G throughput (V_{Sp}) [4.4mins - 264 Seconds traces]. [t=60 ms.]

We exemplify how the variability of configuration contributes to 5G throughput variability using Vodafone Spain, V_{Sp}. Figure 13 shows the time-series plots of 5G throughput, MCS, and MIMO layers over a period of about 4 minutes. The data traces come from V_{Sp} and are plotted at the time granularity of 60 ms. We observe that lower MCS and MIMO layers lead to lower throughput and variability in MCS and MIMO layers contribute to throughput variability (comparing, for example, the first 120 seconds with the

[5] Our definition is inspired by the notion of *bounded variation* in mathematical analysis [3]. We also remark that in video streaming, *smoothness* is measured by $V(t)$ with a fixed time scale, namely, the time scale of video chunks, e.g., t = 4 seconds.

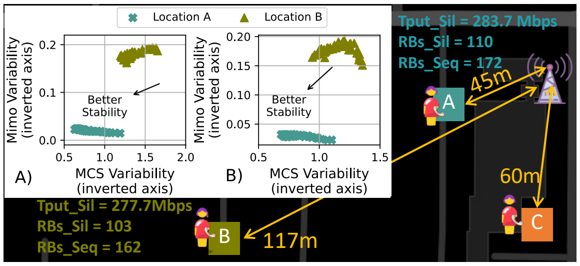

Figure 14: Variability between different users in the same cell (Location A is 45 meters away and Location B is 117 meters from the gNB)

last 120 seconds). For comparison, we also plot the number of RBs allocated per 60 ms at the bottom of the figure. We see that while there are some fluctuations in the RB allocation in the first 120 seconds, the overall variability is far less (more RB allocations staying above 200) when compared with the MCS and MIMO layer parameters. Hence, RB allocation tends to contribute less to 5G throughput variability.

5.2 Variability across Locations and Users

We further investigate 5G channel variability across locations within a cell and when there are multiple users. For these analyses, we conduct repeated measurements by selecting multiple locations within a cell and with multiple UEs located in different locations. Connecting to the same cell, we conduct two sets of measurements (*e.g.,* using iPerf to measure 5G throughput): Sequentially, one location at a time and simultaneously, all locations at the same time.

Using a U.S. operator as an example, Figure 14 depicts several sample locations within a cell where we conduct a series of experiments. We choose all sample locations with lines of sight to the gNB, but varying their distances from the gNB. Figure 14A) shows the (joint) variability of MCS and MIMO layers in a 2D-plot at two sample locations, (A) 45 meters away and (B) 117 meters away from the gNB. When the experiments are done sequentially, the average throughput at each location is 595.1 Mbps and 579.5 Mbps, respectively (the throughput variability is not shown – from Figure 12(A), it is directly correlated with MCS & MIMO layer variability). The (average) RB allocation at each location is 172 and 162, respectively. We see that 5G channel variability depends on locations within a cell. While in line of sight, location B is farther and has higher variability than location A making the UE suffering higher path loss and signal fluctuations. On the other hand, the (average) RB allocation at each location is quite similar despite the difference in channel variability.

Figure 14B) shows similar results at the same two locations, but with the UEs conducting experiments simultaneously. We observe that while the channel variability (as measured by the joint variability in MCS and MIMO layers) remains similar to the previous experiment, the throughput measured by each UE is roughly reduced by half to be 283.7 Mbps and 277.7 Mbps for locations A and B, respectively. This is because the (average) number of RBs allocated to each UE has reduced by about 1/2 to be 110 and 103. We conclude that the number of active users in a cell does not directly affect the channel variability. It does impact the (average) throughput per UE due to resource competition, which is expected.

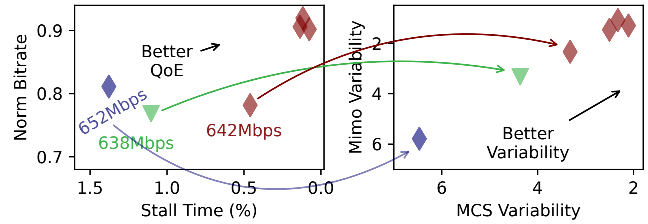

Figure 15: Variability Implications on Application QoE [t=150 ms.]

Takeaways §5. The above analysis confirms that the *aggregate* (*e.g.,* averages/distributions of) performance metrics (and associated parameters) are not sufficient in characterizing 5G channels; the *variability* (over time) in these metrics and parameters provides another critical dimension to capture channel dynamics. In §6, we show how 5G channel variability directly affects application QoE.

6 VIDEO STREAMING OVER 5G MID-BAND

In this section, we use video streaming as a key use case to demonstrate the impact of 5G channel characteristics and dynamics on application QoE. In particular, we show that the (aggregate) 5G PHY throughput contributes strongly to the (average) bitrates attained by video ABR algorithms, whereas channel variability greatly affects stall time performance. Based on these insights, we suggest using smaller chunk sizes for better adaptation to channel variability for improved video streaming QoE performance.

Evaluation Methodology. We deploy an Apache server hosting videos in the same country as the UE and use a `DASH.js` [22] video client. We segment the videos into chunks of 4 seconds (this is a common setting, also suggested in [48]) at seven different quality levels using `FFmpeg` with `libx264`. We configure the video chunks required bandwidth to range from ≈ 30 Mbps, 60 Mbps, 75 Mbps, 200 Mbps, 400 Mbps, 600 Mbps, and 750 Mbps, represented by quality levels from [0, 6] chosen based on the average operator throughput of about 400 Mbps. For the ABR algorithms, we employ BOLA [72], throughput-based [50], and dynamic bitrate algorithms[6]. In our evaluation, we play the video on the UE while running XCAL to collect PHY layer configuration parameters. Our evaluation metrics include the client buffer level, normalized bitrate, and stall time. In our experiments, we note that BOLA generally performs the best among all ABR algorithms (see Figure 24 in Appendix 10.4). Thus, we resort to BOLA for our analysis below.

6.1 PHY Layer Impact on Application QoE

In Figure 15, we show six representative results from video streaming experiments conducted at different times using two European operators, V_{It} and O_{Sp}. These experiments are conducted when the UE is stationary (see §7 for mobility results). In Figure 15 (left plot), video streaming QoE measured in terms of average normalized bitrate and average stall time is shown for each experiment. The average 5G throughput measured during each experiment is also annotated in the figure. The right plot shows the corresponding channel dynamics characterized using (joint) variability in MCS

[6]We have also used L2A [43] and LoLP [19], the results of which are not included in this paper.

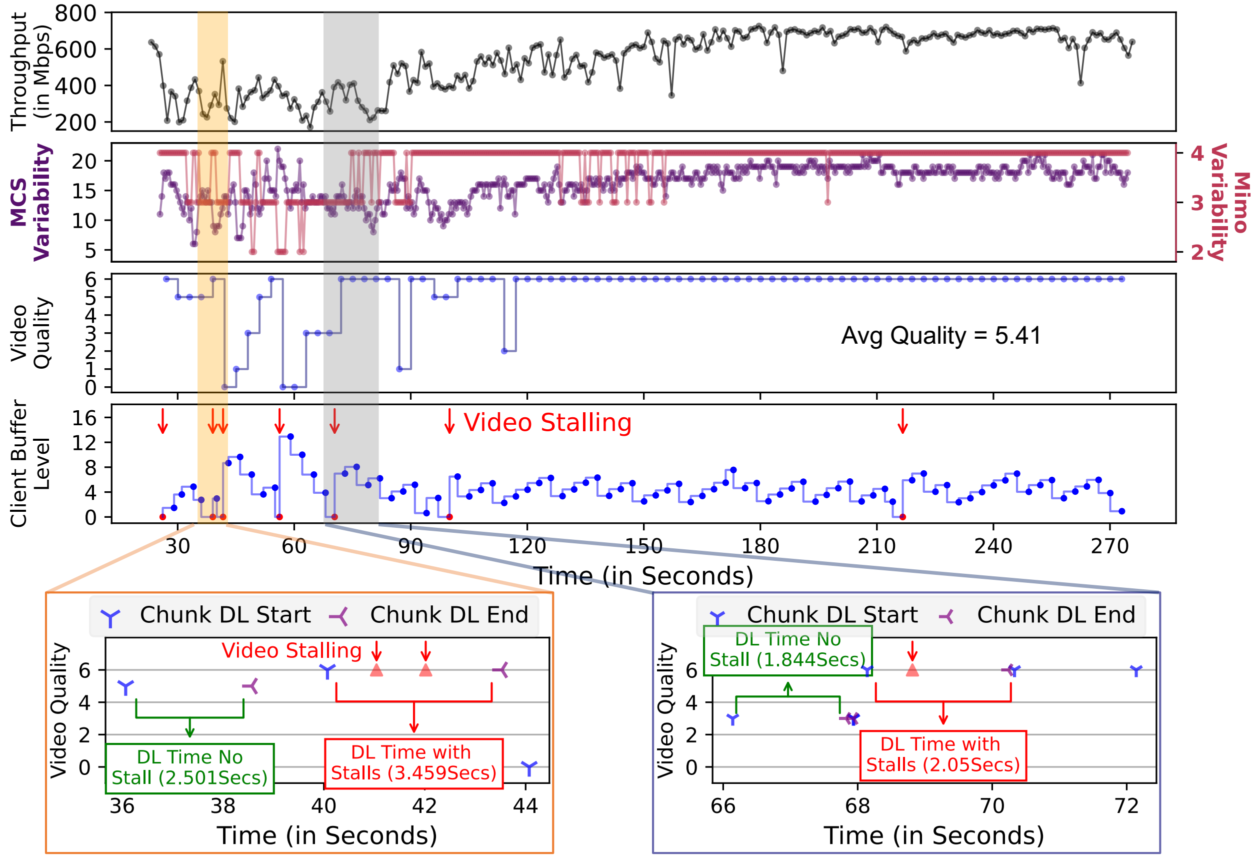

Figure 16: Impact of Throughput Variability on QoE (V_{Sp})

and MIMO layers (calculated at 150 ms time scale). As the arrows across the two figures clearly indicate, there are strong causal relationships from the 5G throughput and channel variability to video streaming QoE performance. We see that, in general, higher (average) 5G throughput tends to lead to higher average bitrates. On the other hand, 5G channel variability clearly influences the average stall time performance. In the following, we will use a detailed example to illustrate the impacts of 5G channel dynamics on video streaming QoE. These observations also hold for the experiments we have done using other operators.

Using data collected from one of the video streaming experiments over the V_{Sp} 5G channel, we visually demonstrate how 5G PHY throughput and parameter dynamics directly affect the video streaming QoE and the ABR decision process. The top two plots in Figure 16 show the 5G PHY throughput, the variability of the MCS values (left y-axis in the second plot) and MIMO layers (right y-axis in the second plot), averaged at 60 ms time scale, over a 5-minute time duration. In the next two rows, we show the bitrates of the video chunks (as decided by BOLA) and the client buffer occupancy over the same time period. Video stalls encountered while streaming are marked in red in the buffer occupancy plot. These yield an average bitrate of 5.41 and an average stall time of 9.96%. We see that the initial high 5G throughput leads BOLA to choose the highest bitrate (quality level 6) for the initial video chunks, but the decreasing throughput causes BOLA to gradually lower the bitrates of the subsequent video chunks due to rapidly draining client buffer occupancy. There is a clear lag in the decisions made by BOLA and the actual 5G throughput performance. Clearly, during the time periods when 5G parameters fluctuate frequently, 5G throughput also varies significantly. The channel variability causes BOLA to adapt the bitrates accordingly, oftentimes drastically, *e.g.*, oscillating between quality levels 6 and 0. The time periods when the 5G channel fluctuates significantly are also the periods when the application experiences video stalls.

To further illustrate the interactions between 5G channel dynamics and the ABR decision-making process, we "blow up" the time period surrounding a video stall event. The two insets at the bottom of Figure 16 show two such events. In each inset, we plot the times a video chunk is being fetched, the quality level of the chunk decided by BOLA, the times when the video chunks arrive at the client buffer, and the stall event. We see that video stall happens because of sudden drops in 5G throughput, causing the video chunks to arrive too late. As BOLA makes decisions based on past buffer occupancy data, it cannot foresee future drops in 5G throughput. Hence, erroneous decisions (*e.g.*, fetching a video chunk of high quality) cause video stalls during the periods of 5G channel instability (*i.e.*, high variability).

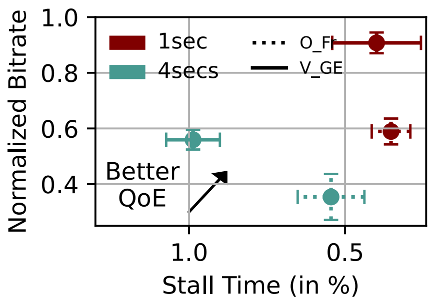

Figure 17: Impact of different video chunk lengths on QoE.

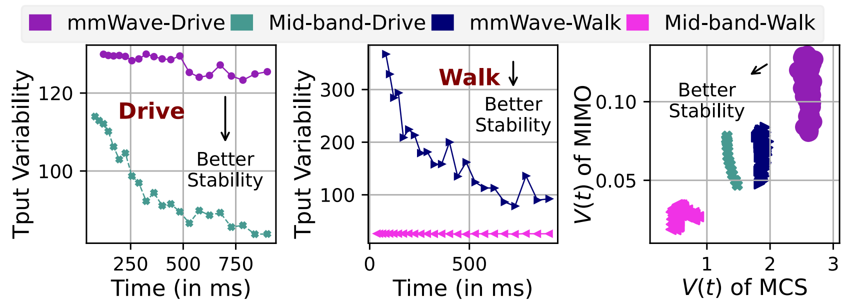

Figure 18: [Driving & Walking] 5G Mid-band vs. mmWave throughput and channel variations.

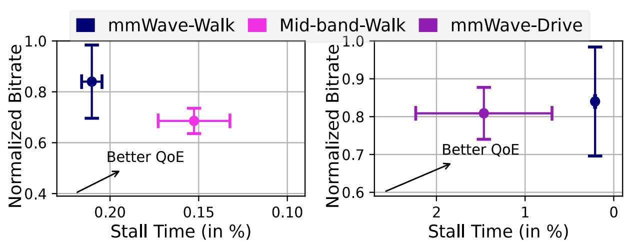

Figure 19: [Driving & Walking] 5G Mid-band vs. mmWave throughput variability impact on video streaming QoE.

6.2 Enhancing ABR Streaming QoE over 5G

Our analysis above suggests a simple, yet effective, approach to potentially improve video streaming QoE, particularly stall times: namely, using smaller video chunk lengths. The basic intuition is enabling the ABR algorithm to make decisions at a shorter time scale to better adapt to 5G channel variability. In Figure 17, we show results obtained using two European operators, O_{Fr} and V_{Ge}, where the experiments are conducted using video chunk lengths of 1 sec vs. 4 sec. We see that by simply using a smaller chunk length, we can effectively improve both the average bitrates achieved and the percentage of stall times. In the case of V_{Ge}, the normalized bitrate is improved from around 0.55 to around 0.9 on average, whereas the percentage of stall times is improved from above 1% down to around 0.4% on average. Similar improvements are achieved in the case of O_{Fr}.

These improvements come from the fact that by using a smaller video chunk length, BOLA can minimize the effect of "erroneous" decisions and adapt to the varying channel conditions faster. For example, if BOLA decides to fetch a video chunk of the highest quality level, the effect of suddenly decreasing 5G throughput will be less likely to cause a 1 sec video chunk to induce a stall event than a 4 secs video chunk; further, BOLA can quickly adjust the quality levels of future video chunks to accommodate the lower throughput. While in this section, we have used video streaming as a case study to illustrate the variability implications on application QoE of 5G, we believe that the general insights apply to other emerging (interactive) applications that aim to attain good QoE through performance-adaptive mechanisms. All in all, it is important to make applications "5G-aware".

7 5G MID-BAND VS. 5G MMWAVE

We conclude our work by briefly comparing the throughput performance and channel dynamics of 5G mid-band vs. 5G mmWave, and their implications on application QoE. This helps elucidate why many consider 5G mid-band as the "sweet spot" of 5G deployment.

PHY Throughput and Channel Variability. Since mmWave 5G is only deployed in the U.S., we conducted experiments using the U.S. operators in selected areas with 5G mid-band and mmWave services. The experiments are performed under several mobility scenarios: stationary, walking, and driving. The aggregate throughput of 5G mid-band vs. 5G mmWave under the two mobility scenarios[7] are: walking 1.6 Gbps, 3.2 Gbps and driving 935.5 Mbps, 1.1 Gbps respectively. Clearly, 5G mmWave offers considerably higher peak and average throughput than 5G mid-band, especially under walking. The difference narrows significantly under driving – this is primarily due to the limited coverage of 5G mmWave: when the UE is moving at a driving speed, 5G mmWave signals deteriorate rapidly and suffer from outages (where the 5G service switches to either 4G or 5G mid-band when available) [31, 57, 58].

Figure 18 shows the throughput and channel variability plots of 5G mmWave vs. mid-band across multiple time scales under both walking and driving. We see that 5G mmWave consistently exhibits significantly higher variability (especially under the smaller time scales) than 5G mid-band. Mobility at driving speeds further induces worsening variability/instability in 5G mmWave channels.

QoE Implications. We now examine the application QoE implications of 5G mid-band vs. 5G mmWave. For this, we conduct two sets of experiments: (a) We use the same video streaming settings as in §6 where video chunks are encoded in 7 quality levels, with an average throughput requirement of around 400 Mbps. Experiments are done using both 5G mid-band and mmWave channels under walking. (b) To take advantage of the notably higher throughput afforded by 5G mmWave, we scale up the resolutions of videos and also encode them at 7 different qualities (*i.e.,* 2.8 Gbps, 2.4 Gbps, 2.0 Gbps, 1.5 Gbps, 1.2 Gbps, 800 Mbps, and 400 Mbps, represented

[7] Prior studies [31, 57, 58, 60] have carried out extensive analysis of 5G mmWave under various mobility scenarios. Since our results regard 5G mid-band performance under (mostly) stationary scenarios in the previous sections, we focus only on the walking and driving scenarios. The performance difference under the stationary scenarios can be gleaned from the prior works and previous sections. Likewise, the 5G latency performance of 5G mmWave and mid-band can be gleaned from the results in §4.3 and [27].

by quality levels from [0, 6]) with an average throughput requirement of around 1.25 Gbps. The experiments are only done over mmWave channels for walking and driving. Our goal here is to explore whether 5G mmWave is capable of effectively supporting ultra-high resolution content streaming. In both (a) and (b), the video chunk length is 1 sec.

Figure 19 [left plot] shows the average bitrate & average stall time for a number of representative traces over 5G mid-band vs. 5G mmWave in scatter-plots for experiment set (a). We see that while 5G mmWave increases the achievable average bitrates overall, the bitrate QoE improvement often comes at the expense of increased stall times when compared with 5G mid-band. This is because 5G mmWave is far more variable than 5G mid-band (41.4% more stable than mmWave while walking, and 42.4% while driving). Figure 19 [right plot] shows the results for experiment set (b). With significantly higher throughput requirements of the scaled-up video streaming application, we see that 5G mmWave struggles to maintain good QoE performance when a user is driving compared to walking. The average bitrate achieved is only 80.8% of the average throughput of the 5G mmWave channel; the average stall time also degrades considerably when compared with streaming of lower-resolution content. These results partially substantiate the sentiment of “disappointment” in 5G (5G mmWave in particular) that has been expressed in the public press [47, 56].

8 RELATED WORK

A significant body of literature has emerged regarding measurement studies in the realm of 5G since its commercial launch in 2019. The majority of these studies have concentrated on 5G deployments, with a particular emphasis on mmWave 5G, predominantly within the United States. These studies have revealed crucial insights concerning coverage, latency, throughput, and application performance [20, 27, 31, 36, 51, 57–60, 66–69, 76–78]. In contrast, there is a limited volume of literature pertaining to measurement studies carried out in European contexts [28, 46, 63, 66]. To the best of our knowledge, there exist no comprehensive and comparative studies on 5G in both the U.S. and Europe, in particular with regard to the now widespread 5G mid-band deployments. To this extent, this paper fills an important gap.

Prior to 5G, there have been a myriad of measurement platforms and studies focusing on 4G LTE network characteristics, performance, latency and configurations. Particularly, several measurement platforms have yield important insights in 4G cellular networks in Europe [17]: The Netradar in Finland [71], Portolan in Italy [25], and MONROE [44], a distributed measurement platform across several countries. In the U.S. [26, 37, 64, 65, 70] have studied 3G and 4G cellular operators from various angles; network usage, performance, infrastructure, resource allocation, and cross-layer interactions. In terms of cellular parameter configurations, [52, 54] studied several European cellular operators and the impact of configurations on performance and implications on QoE when roaming abroad in Europe. Most recently, our work [42] complements these prior roaming studies and presents an in-depth analysis of 5G mid-band PHY layer parameters configurations and their implications of roaming performance and QoE when traveling abroad.

Some recent papers have investigated 5G network config parameters related to the management of high-band [**?**] and mid-band [28] deployments. The breadth of this work surpasses that of [28] which relies on the open-source tool MobileInsight [49], as it encompasses a wider range of geographical regions and configuration settings. XCAL makes it possible to extract not only (semi-)static and real-time (at sub-second scale) 5G config parameters exchanged between 5G networks and UE. Further, unlike [**?**], our work focuses on 5G mid-band. Other works in this domain aim to comprehend throughput predictability in high-band scenarios [58], physical layer latency [27], mobility management [36], power consumption [60, 76], and the performance implications for specific applications like video streaming [60, 67], or to the broader application ecosystem from the user [51] and carrier perspective [63].

9 CONCLUSION

Our study is the first *cross-continent* and *cross-country* analysis of 5G mid-band deployments in four major European countries: Spain, France, Italy, and Germany with (four unique operators) and the United States (three operators). Through cross-layer data analysis, we compare and study how key 5G mid-band channels and configuration parameters affect 5G performance and application QoE from both network and application perspectives. Additionally, through carefully designed experiments, we compare 5G mid-band with 5G mmWave and quantitatively study why 5G mid-band is partially viewed by many as the "sweet-spot" for 5G deployments. Our findings reveal how various configurations and dynamic parameters, including channel bandwidth, resource blocks, channel conditions, modulation schemes, MIMO, and carrier aggregation, impact performance. This research offers valuable insights for 5G operators, aiding in network optimization. It also guides users, application developers, and cloud providers in informed decision-making regarding carrier selection, application improvement, and server placement. Additionally, our study encourages exploration in emerging areas like artificial intelligence and machine learning (AI/ML) in 5G networks, providing vital insights into the future of mobile networks and applications.

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10 APPENDIX

Appendices are supporting material that has not been peer-reviewed.

10.1 Extracting 5G Mid-Band Channel and Configuration Parameters

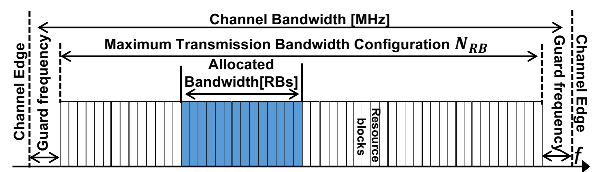

Figure 20: Relationship between channel bandwidth and N_{RB}.

Background about Initial Access Procedure. The UE needs to obtain the master information block (MIB) and system information block (SIB) to connect to the network. The MIB contains the system frame number to start operating with the network (*i.e.,* the *controlResrouceSetZero* and *searchSpaceZero*), and enables the UE to retrieve the allocated SIBs location (in RBs) by looking up Table 12−4 of 3GPP TS38.213 and Table 12−11 of 3GPP TS38.213, respectively [12]. The SIB contains the cell's frequency and access-related information, permitting the UE to camp on. Among the cell information, *absoluteFrequencyPointA*, *offsetToCarrier*, and *carrierBandwidth* help UE identify the frequency channel resources: The *carrierBandwidth* retrieves channel bandwidth from the lookup table 5.3.2−1 [10] in 3GPP TS38.101−1. The *absoluteFrequencyPointA* and *offsetToCarrier* determine the operating frequency channel. Figure 20 shows the relation between the channel bandwidth and N_{RBs}.

Channel Information. We retrieve those parameters via XCAL and locate the 5G mid-band channels used by each mobile operator. We find that Spain Orange and T-Mobile in the U.S. both own 100 MHz (the maximum channel bandwidth in 5G mid-band). Vodafone Spain, and Orange France own 90 MHz. SFR France, Telekom in Germany, and TIM, and Vodafone in Italy, all own 80 MHz. Vodafone Germany, Wind Tre in Italy, and Verizon in the U.S. use 60 MHz, while AT&T owns 40 MHz. Perhaps most interesting, we find that Orange and Vodafone in Spain share a 90 MHz channel bandwidth. As per the Mid-band 5G spectrum auction outcome in Spain [40, 62], we conclude that Orange is using the Vodafone spectrum in our data. Nonetheless, we suspect that both MNOs are in a Reciprocal RAN Sharing agreement [**?**].

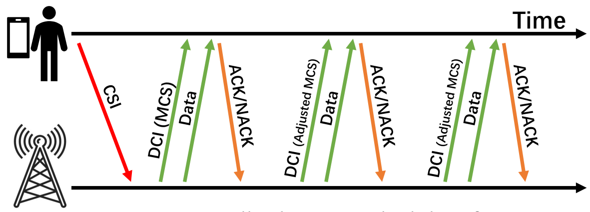

Figure 21: CSI Feedback & DCI scheduling for DL.

10.2 CSI Feedback and DCI scheduling

After access to the network, the UE will periodically (or upon request) transmit the current Channel State Information (CSI) to the gNB. This CSI feedback is averagely sent every tens of milliseconds. Based on the received CSI feedback, along with various other considerations such as traffic load, data queue status, UE priority profiles, and more, the gNB will dynamically determine the configuration for each data transmission (e.g., modulation order, coding rate, MIMO layers). The gNB will then convey this information to the UE using Downlink Control Information (DCI). The UE will provide feedback to the gNB regarding the status of the data packets by sending ACK/NACK feedback. The gNB will also refer to this feedback to adjust the data transmission decisions. Fig. 21 illustrates this communication procedure.

The DCI contains several key parameters, such as the number of layers, the number of RBs within the slot that have been allocated for the UE, and the modulation and coding scheme (MCS) index used. The CSI feedback includes RI (rank indicator), PMI (precode matrix index), CQI (channel quality indicator), and LI (layer indicator), where the latter indicator depends on the previous. Specifically, RI indicates the number of independent data streams that can be simultaneously transmitted; PMI informs the optimal precoding matrix to be used; CQI reports the averaged channel quality and is the key indicator for gNB to decide the modulation and coding scheme (MCS); LI identifies the strongest layer. They altogether configure MIMO.

10.3 Impact of Coverage

To understand the coverage landscape across Orange and Vodafone in Spain, we conduct mobility experiments to understand how many base stations are deployed by each operators around our chosen areas in Madrid. As shown in Figure 22, we find that, O_Sp deployed two base stations while V_Sp deployed three indicated by the gNB ID. In otherwords, O_Sp's gNB are spaced out to cover a larger area, while V_Sp's base stations are closer together in the same area, especially in our chosen locations for testing. The effect of this that V_Sp 90MHz enjoys better signal quality and less interference when compared with O_Sp 90MHz. As a results, V_Sp configures higher MIMO layers, which increases the PHY throughput.

10.4 Variability implications on QoE

As explained in § 6, we use BOLA as the ABR algorithm for video streaming to demonstrate the impact of 5G channel characteristics on application QoE. Figure 24 shows results from measurements conducted in Spain and the U.S. indicating that BOLA shows better QoE in terms of normalized bitrate and stall time compared to throughput-based and dynamic bitrate algorithms.

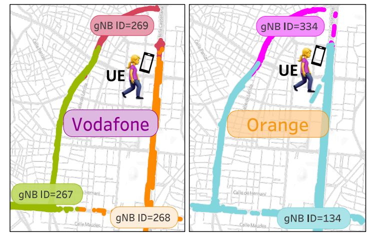

Figure 22: Coverage map of V_{Sp} 90 MHz and O_{Sp} 100 MHz.

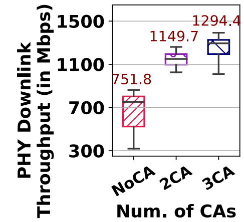

Figure 23: Benefits of CA with TMB

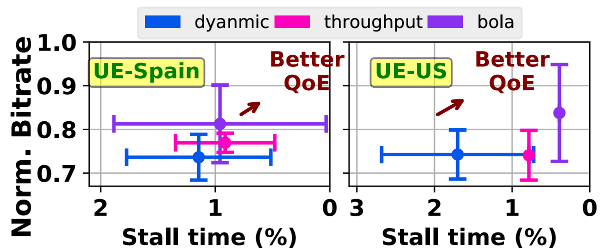

Figure 24: BOLA consistently performs better.

10.5 Impact of CA on Throughput

T-Mobile is unique in its carrier aggregation (CA) capabilities. It can perform CA using (i) two of its n41 channels, yielding an aggregated channel bandwidth of 140 MHz, or (ii) both the n41 TDD channels and n25 FDD channels, yielding, e.g., an aggregated channel bandwidth of 160 MHz with two n41 channels and one 20 MHz n25 channel. The PHY DL throughput performance of using these two CA options is shown in Fig. 4b. We see that CA can significantly boost the PHY DL throughput performance, with an average up to 1.3 Gbps and the maximum close to 1.4 Gbps.

10.6 Summary of Artifacts

We release the artifacts (dataset and tools) associated with this paper at the GitHub repository mentioned below:

https://github.com/SIGCOMM24-5GinMidBands/artifacts

This is a measurement paper with various types of data processed for different purposes having different methodologies. In out GitHub, we group the artifacts by Section number and name. There are README files with each Section folder with more specific instructions to validate our experimental results. Lastly, here are some generic principles we followed for releasing the artifacts:

10.6.1 *Dataset Sizes/Dataset Analysis.*

- If the dataset is small enough, we included the dataset file in this repository itself.
- If the dataset files are huge, we use a small sample of the dataset in the repository to demonstrate the functionality/correctness.
- If data analysis is involved, our instructions will contain information on how to process the data.
- No matter what the dataset size is, we provide the fully generated results and/or plots. If you decide to run the analysis and/or plotting scripts, the outcome of processing will create the raw results files in the repository. Artifacts and Info