IEEE INFOCOM 2024 - IEEE Conference on Computer Communications | 979-8-3503-8350-8/24/$31.00 ©2024 IEEE | DOI: 10.1109/INFOCOM52122.2024.10621234

Roaming across the European Union in the 5G Era: Performance, Challenges, and Opportunities

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***Abstract*—Roaming provides users with voice and data connectivity when traveling abroad. This is particularly the case in Europe where the "Roam like Home" policy established by the European Union in 2017 has made roaming affordable. Nonetheless, due to various policies employed by operators, roaming can incur considerable performance penalties as shown in past studies of 3G/4G networks. As 5G provides significantly higher bandwidth, how does roaming affect user-perceived performance? We present, to the best of our knowledge, the first comprehensive and comparative measurement study of commercial 5G in four European countries.**

Our measurement study is unique in the way it makes it possible to link key 5G mid-band channels and configuration parameters ("policies") used by various operators in these countries with their effect on the observed 5G performance from the network (in particular, the physical and MAC layers) and applications perspectives. Our measurement study not only portrays users' observed quality of experience when roaming, but also provides guidance to optimize the network configuration and to users and application developers in choosing mobile operators. Moreover, our contribution provides the research community with the largest cross-country roaming 5G dataset to stimulate further research.

***Index Terms*—5G Roaming, Mid-band 5G, 5G Throughput, 5G RAN, Roaming, Dataset**

I. Introduction

Roaming has been an integral part of cellular services since the advent of cellular networks, providing voice and data connectivity when users travel abroad. It is particularly important in the European Union (EU) comprising many countries of varying sizes, where people often travel across borders for work, school, visiting families, or tourism. However, due to various policies employed by cellular operators and roaming agreements among them, it has been shown in previous studies [1], [2], [3], [4] that roaming incurs a considerable performance penalty. This is partly due to the *inflated path latency* where traffic from/to a user in a *visited* network in another country must traverse the *home* network in his/her home country (*e.g.,* via the so-called Packet Gateway (PGW) in the case of 4G LTE or the User Plane Function (UPF) in the case of 5G) to connect with the public Internet. In addition, roaming is known to be expensive.

With the overall goal of creating a single digital market, the EU launched the "Roam like Home" initiative in 2017, which has set an end to the roaming surcharges [5]. A survey conducted by the European Commission in 2023 found that thanks to this initiative, a large fraction of users report using the same or more data when roaming abroad (approximately 56 %). However, a quarter of users complain about experiencing a noticeably slower downloading speed [6]. A large-scale experimental study conducted in Europe in 2017-2018 shows that roaming negatively impacts latency which in turn can reduce web browsing experience by up to 150%, quantified by metrics like page load time [4].

Starting in 2019, commercial 5G networks have been gradually rolled out in many parts of the world. In Europe, the predominant 5G services operate in mid-bands (*i.e.,* between 1 GHz and 6 GHz), primarily using channels in the n78 band (3.5 GHz), using the so-called Non-Standalone (NSA) mode. 5G offers significantly higher throughput, especially in the downlink (DL), than 4G LTE, as reported by various recent measurement studies of commercial 5G networks (see, *e.g.,* [7], [8], [9], [10], [11], [12], [13], [14], [15]). We ask how would roaming affect the user's perceived 5G performance? To this end, we carry out the first comparative measurement study of 5G roaming performance in Europe, thus filling a gap in the existing 5G measurement studies. Additionally, what distinguishes our study from previous studies on roaming–which were all conducted in the *pre-5G* era–lies in our abilities to dive into the 5G physical (PHY) and MAC layers and link the key 5G mid-band channel configurations and Quality of Service (QoS) parameters ("roaming policies") used by various operators with their effect on the observed 5G performance.

Our roaming performance study from the *network* perspective, as well as the *application* perspective, is made possible due to our comprehensive measurement platform comprising: *(i)* multiple 5G smartphones – thereafter referred to as user equipment (UE); *(ii)* multiple SIM cards from a total of 8 different 5G operators from three European countries (*i.e.,* France, Italy, and Spain) and roam from three European countries (*i.e.,* France, Germany, and Italy),

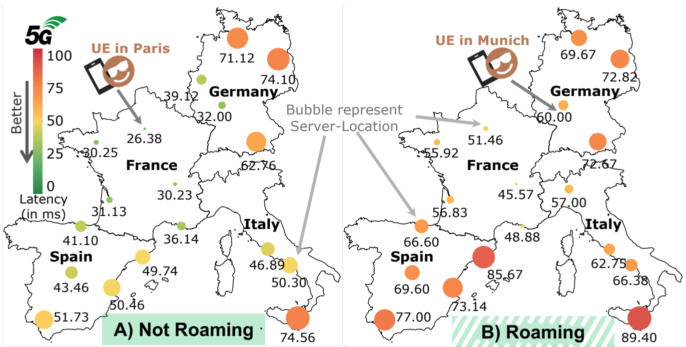


Fig. 1. Round-trip-time measurements to Ookla speedtest servers located in four European countries from UE in Paris, France connected to its home network **[SFR France]** (left) and from UE in Munich, Germany connected to a visited network (right).

(iii) Accuver XCAL [16], a professional 5G measurement tool which collects detailed 5G NR Radio Access Network (RAN) protocol stack information, *(iv)* a set of diverse applications such as iPerf, file download with varying file sizes, and video streaming, and *(v)* carefully selected servers that are located either in the home or visited network country. The details of the measurement methodology are presented in §II. Our data collection spans more than 4400 minutes of network measurements "in the wild", totaling 2+ TB data over 5G.

As our far-reaching goal is to characterize 5G performance when roaming, we exploit our unique measurement dataset to conduct a first-of-its-kind analysis that reveals roaming performance implications to the user-perceived Quality of Service (QoS) and Quality of Experience (QoE) (§III), key insights regarding specific configuration settings on PHY performance when using the default visited network (§IV), and when choosing the visited network (§V). We also study the impact of server placement on roaming performance (§VI). Fig. 1 portrays the breadth of our analysis by showing how latency varies when roaming and non-roaming with SFR France.

The synopsis of contributions of our work are the following:

- We contribute to commercial 5G understanding and conduct the first large-scale, comprehensive, and comparative measurement study of commercial 5G mid-bands roaming in four European countries when the UE is abroad and roaming, filling a gap in the existing 5G measurement studies.
- Our measurement study provides guidance to optimize the network configuration as well as users and application developers in choosing mobile operators when roaming.
- Our work produces the largest EU cross-country roaming 5G mid-band measurement dataset that we know of. We release the dataset and artifacts of our study at https://git2.networks.imdea.org/wng/5g-eu-roaming.

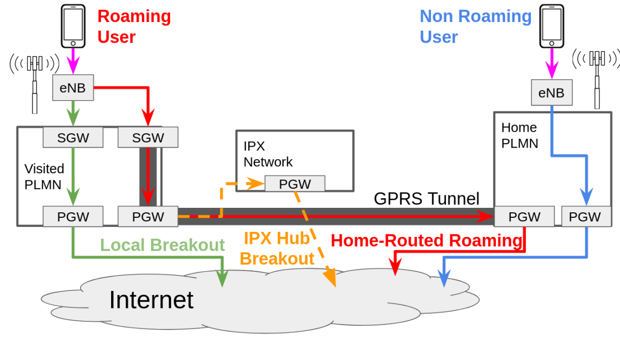


Fig. 2. Mobile network roaming and non-roaming user paths.

II. Background and Measurement Methodology

In this section, we provide some technical background and outline relevant systems, concepts, and terms with respect to mobile 5G roaming and mid-band configuration parameters. We conclude this section by outlining our measurement methodology for data collection.

A. 5G Roaming Terminology and RAN Configuration

As illustrated in Fig. 2, within the roaming sphere, there are two network classifications; Home Public Land Mobile Network (HPLMN) and Visited Public Land Mobile Network, (VPLMN) which make up the infrastructure of home and guest networks for roaming users. A user is considered roaming if he/she accesses a guest network with which the operator has a roaming agreement with the user's home network operator. At home, a user requires a *Home SIM* (*Home Operator*) to access voice and data services on a *Home Network* (*i.e.,* HPLMN). Abroad, *Roaming Users* access mobile services on a *Visited Network* (*i.e.,* VPLMN). Based on the roaming architecture, the *Home SIM* traffic might first be routed to the Packet Data Network Gateway (PGW) of the *Home Network* – Home-routed Roaming (HR), take a short path and breakout through an IP Packet Exchange (IPX) hub – IPX Hub Breakout Roaming (IHBO), or directly exits the mobile network on the *Visited Network* PGW – Local Breakout (LBO), thus might have implications on roaming performance (see §VI).

The VPLMN must control and enforce data restrictions of *Roaming Users'* traffic in accordance with the roaming agreement [17]. In 5G, data restriction is achieved by setting QoS flows that map to Data Radio Bearer (DRB). To deduce which QoS flow map to apply, QoS Identity (QFI) is configured by the base station. The MAC layer is responsible for data differentiation, classification, and prioritization based on the configurations. The network (whether *Home* or *Visited*) configures via *RRC Connection Message* UE-specific DRB channel parameters including the `priority`, `priorisedBitRate`, `bucketSizeDuration` which reflect mapping restrictions and radio resource allocation

TABLE I
5G MID-BAND ROAMING DATASET STATISTICS.

Home Countries	Spain	France	Italy
Home SIMs	Orange Vodafone	Orange SFR	Vodafone
# Unique SIM cards	8		
# Smartphone (Models)	6 (3)		
# Mobile Operators	8		
# Servers Used	122		
Duration	15 Weeks		
5G Network Tests (in minutes)	2800+ notRoaming, 1600+ Roaming		

TABLE II
5G MID-BAND OPERATORS AND ROAMING COUNTRIES.

Roaming Country → **Home Country/Sim ↓**		France	Italy	Germany
Spain	Orange	✓	✓	✓
	Vodafone	✓	✓	
France	Orange		✓	✓
	SFR		✓	✓
Italy	Vodafone			✓

for the *roaming User* traffic. A high numeric `priority` corresponds to high traffic priority [18]. In particular, the number of Physical Resource Blocks (PRBs) allocated to a user is restricted (see §III and §V). A PRB is the basic unit of radio resource allocation (in the frequency domain) by the base station [19]. Thus, a *Roaming User* might be impacted by the *Visited Network* 5G radio configurations.

B. Measurement Methodology and Data Collection

Our analysis is made possible by careful orchestration of data collection that focuses on three dimensions: (1) *countries and 5G operators*, (2) *measurement platform and applications*, and (3) *orchestration of data collection.* We conclude with a summary of our 5G mid-band roaming dataset.

Countries and Carriers. We rely on several related works [9], [13], [14], [20], [21], a few platforms like Ookla speedtest [22] and nperf [23], and fallback on 5G scouting to identify countries/cities with 5G mid-band deployment. In Europe, operators have deployed 5G only in mid (3.3-3.8 GHz, band n78) and low-bands (700 MHz, n28). As our study focuses on mid-band 5G, within each city, we select two locations with excellent 5G coverage for selected major operators. Hence, our study covers 5G mid-band operators in Europe, Spain, France, Italy, and Germany. We select 5G operators within these countries that have the largest market share of subscribers [24], [25]. The operators under study are Société française du radio téléphone (SFR) in France, Deutsche Telekom in Germany, Orange Spain and France, and Vodafone Spain and Italy. All contract SIM cards to avoid any performance throttling. These operators constitute our *Home SIMs*. We use Orange and Vodafone *Home SIMs* from Spain and roam in France, Italy, and Germany, Orange and SFR France *Home SIMs* to roam in Italy and Germany, and Vodafone Italy to roam in Germany.

Application Testing and Measurement Platform. To measure and evaluate mid-band 5G roaming performance from both the *user (application)* and *network perspective* (*i.e.,* PHY and MAC layers), we contrive a comprehensive measurement platform. We attentively select a diverse set of testing servers and applications. For instance, to measure and compare the "raw" user-perceived network performance, particularly the end-to-end (E2E) latency, downlink (DL), and uplink (UL) throughput when a user is at home and connected to the HPLMN and when roaming abroad (on a VPLMN), we take advantage of the Ookla Speedtest servers that are located within the 5G operators' network. Unlike non-contract SIM cards (like pre-paid SIM cards) that may experience network performance throttling, we only use contract SIM cards during our experiments. We also conduct both DL and UL iPerf, Ping, and traceroute experiments. To analyze, and portray the observed QoE of users when at home compared to when roaming, we design and conduct; *(i)* file download experiments with different workload characteristics to mimic various mobile app behaviors, and *(ii)* video streaming experiments. We select servers from three major cloud service providers, namely, Google Cloud Platform (GCP) [26], Microsoft Azure Cloud [27], and Amazon AWS Cloud [28], to run our experiments. Unlike conducting experiments in a *controlled* environment like in a lab setting, conducting experiments *in the wild* clearly poses several challenges. Thus, to ensure consistency across all countries and maintain reliable data collection as much as possible, we developed a variety of customized tools and scripts used for both experiment automation and data collection deployed on each server. Furthermore, to ensure a fair comparison, we use a consistent set of six flagship smartphones including Samsung Galaxy S21 and S21 Ultra across all mobile operators in each country. We use a professional tool, Accuver XCAL [16], to link key 5G mid-band channels and configuration parameters used by the various operators with their impact on the observed 5G performance both when at home and when roaming. XCAL runs on a laptop, can support up to six phones, and provides simultaneous access and data collection to detailed 5G New Radio (NR) control plane and user/data plane information of the PHY layer up to the Radio Resource Control (RRC) layer from the chipset via the Qualcomm Diag (diagnostic interface). When presenting our results, we adopt the *quasi-experimental design* (QED) approach [29] by controlling and conditioning on various parameters such as channel conditions, PRB allocation, and so forth. While we have conducted mobility experiments (where factors like the surrounding people, cars, and buildings are harder to control), in this paper, we present results solely based on our *stationary* experiments.

Data Collection Orchestration. Using our measurement

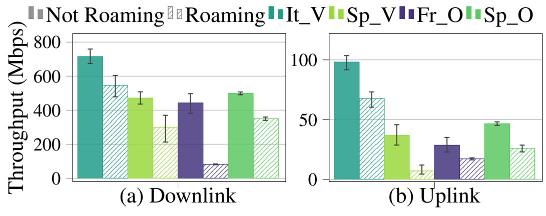


Fig. 3. DL and UL throughput of different operators when at home and roaming abroad.

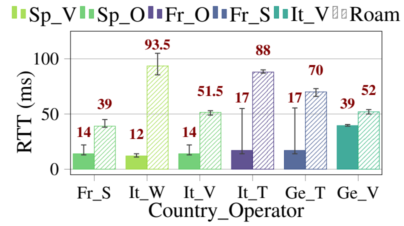


Fig. 4. RTT to a fixed target server from the home network and when roaming abroad.

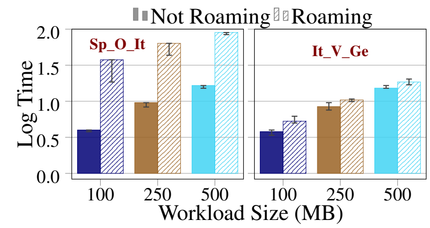


Fig. 5. File download time when Sp_O and It_V are utilized as home network and when roaming.

platform, we have carried out, to the best of our knowledge the largest *cross-country* roaming 5G mid-band measurement campaign. For our data collection, we travel and conduct experiments in a systematic manner in different countries starting from Spain, then France, Italy, and ending in Germany. After scouting 5G coverage in one metropolitan city in each country, we collect detailed logs with XCAL during different days of the week and different times of the day. Based on our financial constraints, we dedicate around 5-10 days for experiments in each country. In a nutshell, we conducted more than 2800 minutes of non-roaming and more than 1600 minutes of roaming measurement of 5G mid-band services between (Oct. 2022 - Dec. 2022) consuming around 2+ TBs. Table I provides an overview of the key details of our measurement campaigns and statistics of the 5G mid-band roaming dataset. Table II shows specific details of which operators we used to roam in which countries.

III. Roaming Performance Implications

In this section, we utilize our collected measurement data to show a comparative analysis of 5G mid-band performance from the user perspective at the application layer. Specifically, we compare the case of roaming and non-roaming for different operators in all considered countries (*i.e.,* France, Germany, Italy, and Spain). We conclude by showing how "raw" application performance metrics translate to the user-perceived QoS and QoE which, to the best of our knowledge, have not been studied yet within the scope of 5G roaming.

A. Roaming Performance

Throughput. In the downlink (DL), we observe a consistent throughput drop across all operators when comparing roaming and non-roaming. Specifically, such a drop in throughput varies for different operators. For instance, Fig. 3(a) shows the user experienced DL throughput when the target server is fixed and it is in the home operator country. As expected, across all scenarios, the DL throughput experienced by a user when roaming is always lower than the DL throughput experienced by that same user when non-roaming. On average a drop of 44% throughput is experienced across all operators, with the largest throughput drop occurring for the case of Orange France roaming in Italy. In contrast, the smallest throughput drop occurs for Vodafone Italy users roaming in Germany. Nonetheless, as expected, users roaming under 5G coverage experience significantly higher throughput (despite the drop) than that of 4G LTE. These results carry performance implications for application QoE that we explore in §III-C.
The uplink tests confirm similar behavior. Fig. 3(b) shows a throughput drop for all operators when roaming in Germany and France averaging an overall 45% drop. There are some notable specific drops. A user with a Vodafone Spain (*i.e.,* Sp_V) SIM card who roams in France experiences an uplink throughput drop of 81% and a user with a Vodafone Italy (*i.e.,* It_V) SIM card who roams in Germany experiences a 30% uplink throughput drop.
Latency. Now, we analyze latency measured as round-trip-time (RTT). For these measurements, the target server is located within the home network with UE(s) roaming on a guest network and contrasted with home network performance. The RTT when roaming and non-roaming, outlined in Fig. 4, demonstrate a clear increase in RTT when roaming across all carriers. The observed average increase is around 69%. However, in some cases, such increase is much lower. For example, the increased RTT for Vodafone in Italy when roaming in Germany (It_V/Ge_V) is only 25%.

B. QoS Implications when Roaming

To investigate the impact of roaming on QoS, we conduct a series of file downloads for different file sizes. The files are stored on a target server located in the *Home SIM*'s country. We perform a sequence of browser-based HTTP downloads at 2 seconds intervals to measure the file download time for roaming and non-roaming cases. We repeat these experiments 20 times.
File Download Performance when Roaming. Fig. 5 shows the file download times for two operators, Orange Spain and Vodafone Italy when non-roaming and when roaming in Italy and Germany respectively. We use several file sizes, *i.e.,* 100 MB, 250 MB, and 500 MB. The target server for Orange Spain is in Spain, Madrid, and the target server for Vodafone Italy is in Rome, Italy. Note that the Y-axis is in the log 10 scale. If we consider the file size of 500 MB, we can see that roaming with Vodafone Italy in Germany achieves a lower file download time of around 20 ms - 25 ms, while roaming with Orange Spain in Italy needs around 64 ms - 100 ms. We also

note that the increase in the file download time when roaming is consistent with Home Routed Roaming (HR) (see §II-A).

C. QoE Implications when Roaming

To understand how the roaming performance translates to the user-perceived QoE, we conduct video streaming experiments for both roaming and non-roaming cases. We divide the video to be transmitted into several chunks of fixed length and encode them with different quality levels. We use `FFmpeg` with `libx264` to encode a 210 seconds video into seven qualities with different bitrates at 30 frames per second (fps) and 4 secs chunk length (this is the suggested length for Adaptive bitrate (ABR) [30]). The bandwidth required to download chunks from the lowest to the highest quality is $\approx$ 30 Mbps, 60 Mbps, 75 Mbps, 200 Mbps, 400 Mbps, 600 Mbps, and 750 Mbps respectively, selected based on the average download throughput for all operators which is $\approx$ 400 Mbps. As the network conditions change, ABR algorithms are used to adapt the quality of the requested chunks to improve QoE. For our experiments, we use `DASH.js` [31], an open-source video streaming system. We test several popular ABR algorithms: (1) BOLA [32], (2) throughput-based [33], and (3) dynamic bitrate algorithms implemented in `DASH.js`. We use a custom HTML-based player to measure the performance of each ABR algorithm across operators and cloud servers. Similar to §III-B, for this section the target server used to host the video is in the home user country. For our results, we normalized the average bitrate[1] of the video chunks and stall time % (*i.e.,* percentage of time spent while waiting for video chunks to be played).

Does 5G's Roaming Impact QoE? Having observed throughput drop and latency increase across all operators in several countries, now we examine the effect on the QoE. Fig. 6 shows the normalized average bitrate (y-axis) and stall time % (x-axis) when streaming using Vodafone and Orange both from Spain when non-roaming and when roaming in Italy. We observe, as expected, higher bitrates and lower stall times for the non-roaming case for all ABR algorithms. Bola outperforms all ABR algorithms in terms of both bitrate and stall time when not roaming. However, all ABR algorithms have similar performance. These results suggest that current ABR algorithms do not play a significant role in QoE when roaming. Further analysis of how specific ABR algorithms perform in roaming is left to future work as it would involve underlying implementation examination. Nonetheless, we observe that roaming negatively affects stall time and bitrate QoE metrics. These stall time results are consistent with the observed increase in latency when roaming as shown earlier in Fig. 1. Similarly, the overall reduced DL throughput is consistent with the overall lower bitrates observed in the ABR tests.

[1] We normalize the bitrate to be in the range $[0 : 1]$ using the bitrate of the highest available quality for the video (quality 7, which requires 750 Mbps).

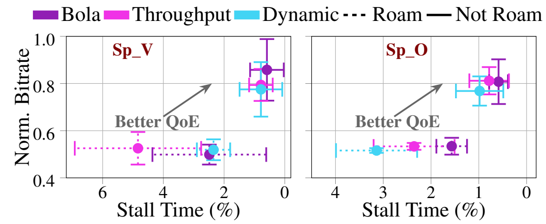


Fig. 6. QoE Performance with Spain Vodafone and Orange when non-roaming and when roaming from Italy.

IV. 5G Configuration Impact on PHY Performance

To understand the roaming performance, we study the following three aspects: *(i)* The effect of different PHY layer configurations on throughput experienced by users when roaming with the default visited network, *(ii)* How a visited network treats roaming users from different countries/operators, and *(iii)* The performance differences that users would perceive by roaming with different operators from the same country towards their home country (*e.g.,* a user with Orange France SIM roaming using Wind Tre and TIM operators from Italy to France). In this section, we study the first aspect and cover the other two in the next section.

PHY layer Throughput. Fig. 7 shows the PHY layer DL throughput of a non-roaming user using Vodafone Spain with respect to a roaming user using Vodafone Spain from France and Italy. Under poor channel conditions (CQI $<$ 12) (see Fig. 7(a)), roaming from France or Italy respectively leads to a throughput of 223.5 Mbps and 190 Mbps. Surprisingly, under good channel conditions (CQI $\geq$ 12) (see Fig. 7(b)), roaming from Italy does not lead to higher throughput than for poor channel conditions as in the case of France (see Fig. 7(a)). While Italy achieves 191.3 Mbps, France achieves 332.2 Mbps which represents an increase of 48.6%. As expected, the achievable throughput is significantly lower for roaming than for the non-roaming case that we include in Fig. 7 as a baseline comparison. For example, the throughput drops under good channel conditions are 73% and 53% for Italy and France respectively.

Digging deeper to understand the difference in the PHY layer throughput performance, we find that the visited Network assigns a different priority (*i.e.,* less) to roaming users than home users. Fig. 8 shows the different radio bearer configuration parameters (`priority`, `priorisedBitRate`, and `bucketSizeDuration`) assigned to a Vodafone Spain SIM user by different operators[2]. We observe that Vodafone Spain SIM traffic is assigned the highest priority by its home network Vodafone Spain as [13, 8 kBps, 300 ms], while when roaming it is assigned by SFR

[2] To achieve the `priorisedBitRate`, a variable B_j is computed based on the time elapse since the last B_j update. If $B_j \geq BucketSize$ = `priorisedBitRate` $\times$ `bucketSizeDuration`, then B_j = `bucketSizeDuration` [34].

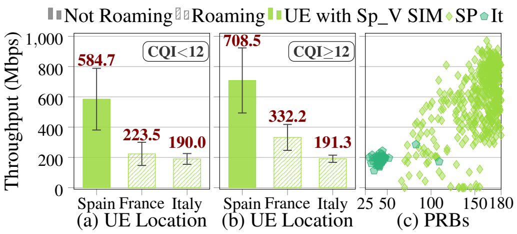


Fig. 7. PHY DL Throughput and PRBs allocated for Vodafone Spain at home and roaming in France and Italy.

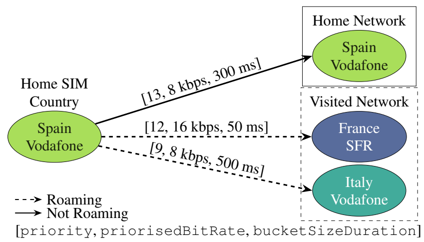


Fig. 8. 5G NR DRB configurations when roaming and not roaming.

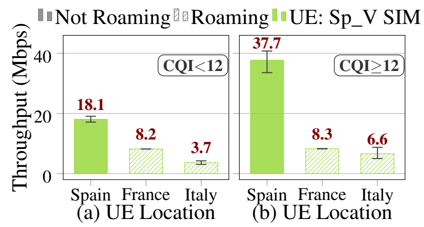


Fig. 9. PHY UL Throughput for Vodafone Spain at home and roaming in France and Italy.

TABLE III
RADIO BEARER CONFIGURATION PARAMETERS ASSIGNED TO HOME AND ROAMING TRAFFIC BY DIFFERENT OPERATORS

Operator →	Spain (Sp_Org)			Spain (Sp_Vod)			France (Fr_Org)		France (Fr_SFR)		Italy (It_Vod)	
UE_location →	Spain	France	Italy	Spain	France	Italy	France	Italy	France	Germany	Italy	Germany
`priority`	13	10	10	13	12	9	10	9	12	11	13	12
`prioritisedBitrate` (in kBps)	8	8	8	8	16	8	8	8	16	8	64	8
`bucketSizeDuration` (in ms)	300	50	50	300	50	500	50	500	50	50	100	300

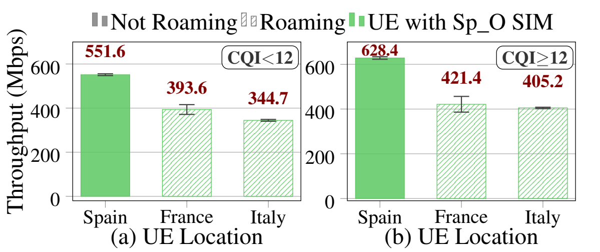


Fig. 10. PHY DL throughput for Orange Spain when home or roaming.

France [12, 16 kBps, 50 ms] and by Vodafone Italy [9, 8 kBps, 500 ms] as the `priority`, `priorisedBitRate`, and `bucketSizeDuration` respectively, which is in line with the throughput values shown in Fig. 7. Moreover, we would like to point out that roaming users' traffic is treated differently by different operators. For example, the same Vodafone Spain user's traffic is assigned a higher priority by SFR France compared to Vodafone Italy, and thus experiences a higher throughput of 332.2 Mbps on average compared to 191.3 Mbps under good channel conditions (CQI $\geq$ 12) while roaming in France and Italy respectively as shown in Fig. 7(b). This could be attributed to the different contracts between operators across countries.

To confirm our conclusion, we conduct a comparative analysis of the number of PRBs assigned and the PHY layer throughput experienced. Fig. 7(c) shows the corresponding PRBs allocated by each operator under good channel conditions (CQI $\geq$12). We observe that the maximum number of PRBs allocated by Vodafone Italy is 109, by SFR France is 152 (not shown in Fig. 7(c)), and by Vodafone Spain is 180 which directly translates to the DL PHY layer throughput experienced in each case. Similar conclusions can be drawn for UL PHY layer throughput for the same scenario as shown in Fig. 9.

Finally, these results are also observed amongst other operators as Table III shows the DRB configuration parameters assigned to the traffic of each operator at home (first column) and while roaming in other countries as assigned by visited networks. We can see each traffic is assigned the highest priority in its home country and less priority when roaming. Another example confirming the same conclusion is in Fig. 10 where the traffic of an Orange Spain's user is assigned the same priority [10, 8 kBps, 50 ms] while roaming in France and Italy, but less than in Spain as shown in Table III. Thus, the experienced throughput while roaming is comparable as 421.4 Mbps and 405.2 Mbps for France and Italy respectively, and 628.4 Mbps in Spain under good channel conditions (see Fig. 10(b)). Our results suggest that operators have different roaming arrangements with other operators and countries. For individuals who frequently travel, careful selection of a Visited Network may considerably improve the QoS experienced. We will provide a deeper analysis in our discussion in §V.

V. ROAMING PERFORMANCE WITHIN A COUNTRY

After having gained insights about roaming performance when using the default visited network, we now dig deeper and build on the observation that a user can manually select the visited network to roam from. Hence, in this section, we seek to answer two questions: *(1)* Do visited networks share the same PHY layer configurations when providing service to users roaming from different operators/countries? *(network perspective)*, and *(2)* what are the performance gains attainable by careful selection of the visited network within the same country *(user perspective)*. We present the case of users roaming in Italy with visited network options of Wind Tre and TIM and for home networks Orange Spain and Orange France.

A. Network Side: How does an operator configure different roaming users?

For this scenario, we conduct bulk data downloads with Orange France and Orange Spain and force both SIM cards

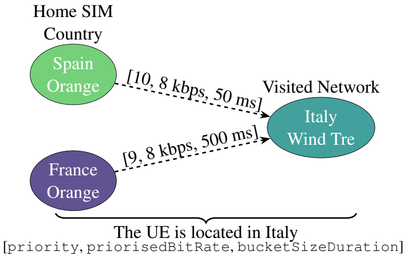


Fig. 11. **[From Network Side]** 5G NR DRB configuration of Orange Spain and France roaming with Wind Tre.

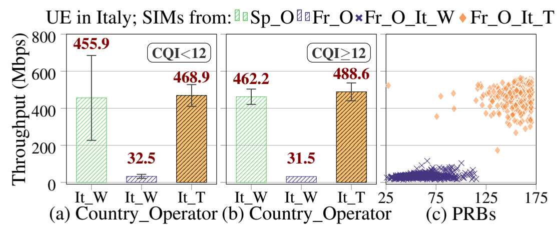


Fig. 12. Comparing the PHY DL Throughput when; 1) Orange France and Spain roam with Wind Tre and 2) when Orange France roams with Wind Tre and TIM in Italy.

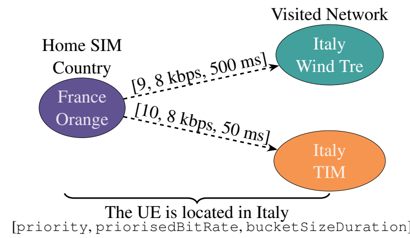


Fig. 13. **[From User Side]** 5G NR DRB configuration of Orange France roaming on Wind Tre and TIM.

to roam with Wind Tre operator in Italy. We note that the default Visited Networks for both Orange France and Orange Spain in Italy is TIM and Wind Tre respectively. Fig. 11 shows the DRB configuration parameters for each case: Wind Tre configures Orange Spain and Orange France with [10, 8 kBps, 50 ms] and [9, 8 kBps, 500 ms] respectively. Hence, as discussed in §IV, we expect Orange Spain users to have a higher throughput which is confirmed by the results for poor (Fig. 12(a)) and good (Fig. 12(b)) channel conditions. We can notice that the DL PHY layer throughput for Orange Spain is around 462.2 Mbps on average compared to just 31.5 Mbps for Orange France under good channel conditions (CQI $\geq$12, see Fig. 12(b)). Our experimental results suggest that, despite the "Roam Like Home" initiative [35], roaming agreements vary across carriers and countries.

B. User Side: Understanding the effect of deliberately roaming with different operators in the same country.

Since the throughput for Orange France roaming with the Wind Tre was pretty low, we forced it to connect to another Visited Network in Italy to compare the performance. We manually change the visited network setting on the smartphone by first opening the Android Settings and subsequently navigating to Connections → Mobile Networks → Network Operators, then disabling the "Select Automatically" Option. This allows a user to manually set which visited network he/she will roam with. In case 1, we set Orange France to roam with Wind Tre, and in case 2, TIM. We conduct bulk data downloads from a server also located in Rome, Italy. Fig. 13 shows the DRB configuration parameters assigned to Orange France by Wind Tre and TIM. We observe that different radio bearer configuration parameters are configured by each operator. Wind Tre configures Orange France with [9, 8 kBps, 500 ms] while TIM assigns [10, 8 kBps, 50 ms] as the `priority`, `priorisedBitRate`, and `bucketSizeDuration` respectively. Hence, we expect Orange France to have better performance while roaming with TIM as shown in Fig. 12. Under good channel conditions (CQI $\geq$12) Orange France users roaming with TIM experience an average of 488.6 Mbps compared to 31.5 Mbps while

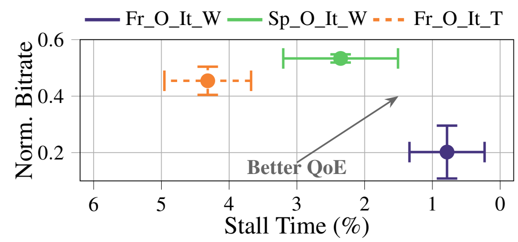


Fig. 14. QoE when roaming in Italy with different visited networks.

roaming with Wind Tre which represents an improvement of (15×). This is also confirmed by the corresponding maximum number of PRBs allocated in each case, 116 and 170 for Wind Tre and TIM respectively (see Fig. 12(c)).

Finally, this difference in DL throughput is also reflected in the QoE experience as we can see in Fig. 14. Orange France users experience a better QoE when roaming with TIM vs Wind Tre, and Orange Spain users have better QoE than Orange France when they both roam with Wind Tre. These results are in line with the priorities defined for each case and are also observed among other operators. Hence, Our results suggest that operators have different roaming arrangements with other operators and countries. For individuals who frequently travel, a careful selection of Visited Networks may considerably improve the QoS and QoE experienced.

VI. Server Placement Impact on Roaming Performance

In this section, we study the impact of server placement on roaming performance. First, we describe our measurement setup and data collection, second, we quantify the impact of roaming on the PHY layer latency, and conclude with the roaming overall impact on E2E latency to different servers.

Measurement Setup: Using our experimental platform as outlined earlier in §II, we conduct both traceroute and ping experiments to all the servers we deployed in each country including the Ookla SpeedTest servers. We repeat these experiments 20 times for each target server per operator. Our resulting dataset includes $1,711$ traceroute files and $18,821$ public IP addresses identified.

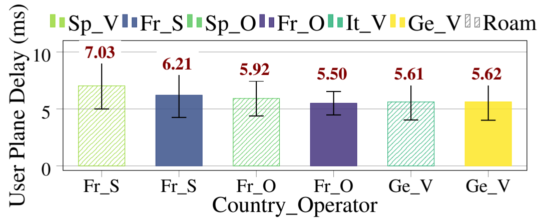


Fig. 15. PHY layer latency when at home and roaming with different operators across several countries.

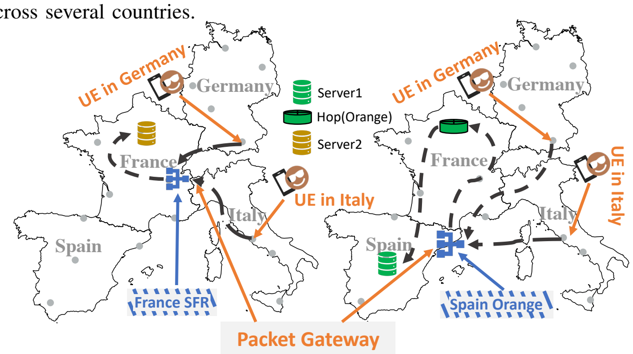


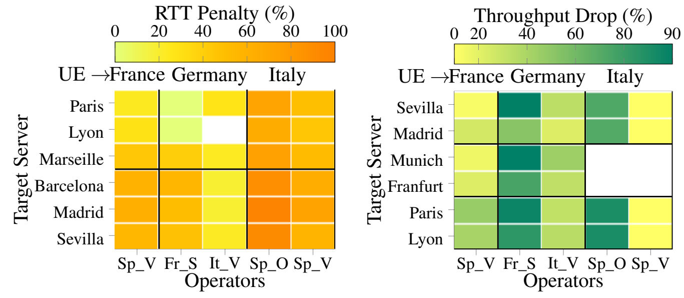
Fig. 16. Data path and transit gateway location when roaming with SFR France and Orange Spain in Germany and Italy. For SFR France, the packet gateway location is Grenoble, France, and for Orange Spain is Barcelona, Spain.

A. Roaming impact on PHY Latency

To understand the effect of server location on latency when roaming, we first study the impact of roaming on the PHY layer delay. Similar to [15], we leverage the detailed 5G NR PHY layer interactions exposed by XCAL to quantify the delay on the PHY layer. Fig. 15 shows the PHY layer latency when roaming and not, for example, `Sp_V` & `Fr_S` (Vodafone Spain roams through the default visited Network SFR France) and we compare its PHY layer latency with `Fr_S` & `Fr_S` (SFR France which uses its home network in France). The location of the target server has no impact on the PHY layer latency in this context as also mentioned in [15]. Surprisingly, our results show that the difference in latency on the PHY layer when roaming and not is very small. That is, we observe a maximum increase in latency by 13% (0.82 ms) on the PHY layer for roaming users compared to non-roaming users. These results are due to the shorter *slot* numerology in 5G NR, where a *slot* time drops from 1 ms in 4G LTE to 0.5 ms in 5G [19]. Thus, although roaming traffic is less prioritized than non-roaming traffic (as shown earlier), the effect on the PHY latency is rather insignificant because of the shorter *slot* times.

B. Roaming Performance Implications

Delay Implications. We use *asn* [36] tool to learn the IP addresses of the infrastructure elements along the data path of roaming users and compare them with home users towards the same target servers in various locations. By comparing the set of the first three hops in traceroute when a user is roaming and not, we find that the roaming traffic is treated differently,



(a) E2E latency penalty (b) Throughput penalty

Fig. 17. Analysis of latency and throughput penalties when roaming with several operators in France, Germany, and Italy.

particularly in terms of transit gateway selection. We note that this observation is different from Mandalari *et al.* roaming study [2], conducted in 2017 pre-5G era. For instance, as shown in Fig. 16 on the left, we observe that when a user is using SFR France at home, our geolocation analysis consistently reveals the first three hops are in Paris, France, whereas when the user is roaming in Germany, the first three hops are located in Grenoble, France in the south before going to the target server in Paris up north. Another example is when a user is using Orange Spain (see Fig. 16 on the right), the traffic when a user is at home (not roaming) points to the Madrid, Spain transit gateway `bundle-ether101-14.madtr6.madrid.opentransit.net`, and when the user is roaming in Germany, the traffic is sent to the Barcelona, Spain, transit gateway `bundle-ether102-14.bartr2.barcelona.opentransit.net` before going to the target server in Madrid. Further analysis using SFR France and Orange Spain when the user is roaming in Italy instead of Germany, the traffic is also always routed to Grenoble, France and Barcelona, Spain transit gateways respectively (see Fig. 16).

To investigate the differential roaming traffic treatment implications on latency, we compute the *delay penalty* – the difference between the median delay to reach a given server when at home and the median delay to reach the same server when roaming. Fig. 17a exemplifies these delays for Vodafone Spain, SFR France, Vodafone Italy, Orange Spain, and Vodafone Spain when roaming in France, Germany, and Italy. We note that the delay penalty varies widely as a function of the roaming location and distance to the server. Our dataset shows that the smallest penalty occurs with SFR France and Vodafone Italy when roaming in Germany. The largest delay penalty occurs with Orange Spain when roaming in Italy. This is because, the roaming traffic is consistently routed from the Barcelona, Spain transit gateway to Paris, France first, before reaching the target server in Spain. We suspect that this is due to the fact that Orange is primarily a French company. This further suggests that the GTP tunnel established between the SGW of the `visited Network` and the PGW of the home network might be slower than the available Internet path.

Throughput Implications. Lastly Fig. 17b shows the percentage *Throughput drop*, which illustrates the variance in throughput when a user is roaming and when at home to the same target server for different operators. We note that the lowest drop occurs when Vodafone Spain is roaming in France and Italy, and the largest drop occurs when SFR France is roaming in Germany. We point out that, two operators from the same country experience varied levels of throughput drops when connecting to the same destination server. For example, when a user travels to Italy and uses Orange Spain and Vodafone Spain, the latter generally incurs lower throughput drops regardless of the location of the target server, further justifying and supporting our findings from §III, §IV, and §V.

VII. Related Work

Relevant to our work are both measurement studies on 5G networks and on roaming. We first dive deep into the first category and next overview the literature for the second.

5G Measurement Studies. There is a wealth of literature on measurement studies that analyze 5G performance. The vast majority of these studies have been carried out in the U.S. and uncovered key aspects related to coverage, latency, throughput, and application performance [12], [7], [8], [13], [14], [37], [38], [39], [40], [15], [41], [42]. The literature on measurement studies in Europe is comparatively thinner [8], [9], [10], [11]. None of the above work has focused on roaming, hence our work fills an important gap.

Some recent papers have investigated 5G network configuration parameters related to the management of FR2 [39] and FR1 mid-band [9] deployments. Similarly to [39], we also use XCAL as it makes it possible to extract not only (semi-)static 5G configuration parameters, but also detailed dynamic parameters exchanged between the 5G networks and UE. In contrast, the work in [9] relies on the open-source tool MobileInsight [43]. Hence, the breadth of our work surpasses that of [39], [9] as it encompasses a wider range of countries and carriers, and the configuration settings we analyze are roaming specific.

Other studies aim at understanding throughput predictability at high-bands [13], physical layer latency [15], mobility management [40], power consumption [7], [14] as well as performance implications to specific applications like video streaming [14], [37], or to the broader application ecosystem from the user [41] and carrier perspective [11]. Finally, additional studies analyze the dynamics of power management [7] under different mobility patterns [14].

Roaming Measurement Studies. The literature on measurement studies that focus on roaming is thin and mainly focused on Europe [1], [2], [3], [4], partly due to the potentially high costs and challenging coordination efforts required to carry out such large measurement studies. A significant fraction of the literature exploits the MONROE platform [44], a large platform for mobile broadband measurements and testbed activities. For example, [4], [2], [3] are all studies executed with MONROE and, in contrast to our work, they do not focus on 5G neither exploit low-level configuration parameters to identify the root causes of higher layer performance.

VIII. Concluding Remarks

In this paper, we presented - to the best of our knowledge - the first comparative measurement study of 5G roaming performance. Our study covers 8 European 5G operators in 4 different EU countries. With a carefully designed measurement methodology, we conducted extensive data collection campaigns totaling more than 2 TB over 5G testing several applications, including file download and video streaming. The analysis of our extensive dataset makes it possible to uncover the key 5G mid-band channels and configuration parameters (*i.e.,* "policies") employed by various operators when roaming. A key distinct feature of our study is that we relate the major factors that impact the observed 5G performance both from the network (physical layer) perspective as well as the application perspective with configuration specifications. In particular, we show how the QoS policies adopted by visited network operators can have a significant impact on the perceived 5G performance of a roaming user. On the one hand, visited network operators may treat roaming users from two foreign operators differently. On the other hand, our study reveals that by understanding the QoS policies employed by visited networks, a user may be able to select a different visited network to use for better roaming performance. Due to the inflated path latency, server placement/selection is also crucial to guarantee QoE to users when roaming.

The authors have provided public access to their code and/or data at https://git2.networks.imdea.org/wng/5g-eu-roaming.

Acknowledgment

We thank the anonymous reviewers for their suggestions and feedback. We also thank Dr. Domenico Giustiniano from IMDEA Networks, Prof. Stefania Bartoletti from the Department of Electronic Engineering University of Rome, Tor Vergata, Dr.-Ing. Jörg Ott and Hendrik Cech from the Technical University of Munich, and Dr. Roger J. L. NGUELE MEKE for providing us with contract SIM cards, and other equipment and tools to make our measurement study possible. This research was supported in part by NSF under Grants 1814322, 1831140, 1836772, 2128489, 2220286, 2220292, and 2321531 as well as a Cisco grant, UMN College of Science and Engineering InterS&Ection seed grant, and by the Spanish Ministry of Science and Innovation through the Juan de la Cierva grant IJC2019-039885-I and PID2021-128250NB-I00 ("bRAIN").

REFERENCES

[1] N. Vallina-Rodriguez, S. Sundaresan, C. Kreibich, N. Weaver, and V. Paxson, “Beyond the radio: Illuminating the higher layers of mobile networks,” in *Proc. of ACM MobiSys*, 2015, p. 375–387.

[2] A. M. Mandalari, A. Lutu, A. Custura, A. Safari Khatouni, Ö. Alay, M. Bagnulo, V. Bajpai, A. Brunstrom, J. Ott, M. Mellia *et al.*, “Experience: Implications of roaming in Europe,” in *Proc. of ACM MobiCom*, 2018, pp. 179–189.

[3] F. Michclinakis, H. Doroud, A. Razaghpanah, A. Lutu, N. Vallina-Rodriguez, P. Gill, and J. Widmer, “The cloud that runs the mobile Internet: A measurement study of mobile cloud services,” in *Proc. of IEEE INFOCOM*, 2018, pp. 1619–1627.

[4] A. Mandalari, A. Lutu, A. Custura, A. Khatouni, and et al., “Measuring roaming in Europe: Infrastructure and implications on users’ QoE,” *IEEE Transactions on Mobile Computing*, vol. 21, no. 10, pp. 3687–3699, 2022.

[5] E. Commission, “New rules on roaming charges and open internet,” Jun 2017. [Online]. Available: https://digital-strategy.ec.europa.eu/en/news/new-rules-roaming-charges-and-open-internet

[6] E. Commission, “Roaming,” Jul 2023, Accessed on Jan 12, 2024: https://europa.eu/eurobarometer/surveys/detail/2958.

[7] D. Xu, A. Zhou, X. Zhang, G. Wang, X. Liu, C. An, Y. Shi, L. Liu, and H. Ma, “Understanding operational 5G: A first measurement study on its coverage, performance and energy consumption,” in *Proc. of ACM SIGCOMM*, 2020, p. 479–494.

[8] D. Raca, D. Leahy, C. J. Sreenan, and J. J. Quinlan, “Beyond throughput, the next generation: A 5G dataset with channel and context metrics,” in *Proc. of ACM MMSys*, 2020, p. 303–308.

[9] C. Fiandrino, D. Juárez Martínez-Villanueva, and J. Widmer, “Uncovering 5g performance on public transit systems with an app-based measurement study,” in *Proc. ACM MSWIM*, 2022, pp. 65–73.

[10] K. Kousias, M. Rajiullah, and et al., “Coverage and performance analysis of 5G non-standalone deployments,” in *Proc. of ACM WiNTECH*, 2022.

[11] P. Parastar, A. Lutu, O. Alay, G. Caso, and D. Perino, “Spotlight on 5G: Performance, device evolution and challenges from a mobile operator perspective,” in *Proc. of IEEE INFOCOM*, 2023, pp. 1–10.

[12] A. Narayanan, E. Ramadan, J. Carpenter, Q. Liu, Y. Liu, F. Qian, and Z.-L. Zhang, “A first look at commercial 5G performance on smartphones,” in *Proc. of The Web Conference*, 2020, p. 894–905.

[13] A. Narayanan, E. Ramadan, R. Mehta, X. Hu, Q. Liu, R. A. Fezeu, U. K. Dayalan, S. Verma, P. Ji, T. Li *et al.*, “Lumos5g: Mapping and predicting commercial mmwave 5g throughput,” in *Proceedings of the ACM Internet Measurement Conference*, 2020, pp. 176–193.

[14] A. Narayanan, X. Zhang, R. Zhu, A. Hassan, S. Jin, X. Zhu, X. Zhang, D. Rybkin, Z. Yang, Z. M. Mao *et al.*, “A variegated look at 5g in the wild: performance, power, and qoe implications,” in *Proc of ACM SIGCOMM*, 2021, pp. 610–625.

[15] R. A. K. Fezeu, E. Ramadan, and et al., “An in-depth measurement analysis of 5G mmwave PHY latency and its impact on end-to-end delay,” in *Passive and Active Measurement*, A. Brunstrom, M. Flores, and M. Fiore, Eds. Cham: Springer Nature Switzerland, 2023, pp. 284–312.

[16] Accuver, accessed on Jan 12, 2024. [Online]. Available: https://www.accuver.com/sub/products/view.php?idx=6

[17] R. Keller, D. Castellanos, A. Sander, A. Robison, and A. Abtin, “Roaming in the 5g system: The 5gs roaming architecture,” *Ericsson Technology Review*, vol. 2021, no. 6, p. 2–11, Jun 2021.

[18] 3GPP, “5g; system architecture for the 5g system (5gs) (3gpp ts 23.501 version 17.5.0 release 17),” https://www.etsi.org/deliver/etsi_ts/123500_123599/123501/17.05.00_60/ts_123501v170500p.pdf, 2022.

[19] 3GPP, “5G; NR; Physical channels and modulation (3GPP TS 38.211 version 16.2.0 Release 16),” https://www.etsi.org/deliver/etsi_ts/138200_138299/138211/16.02.00_60/ts_138211v160200p.pdf, July 2020.

[20] M. Ghoshal, Z. J. Kong, and et al., “An in-depth study of uplink performance of 5G mmwave networks,” in *Proc. of ACM SIGCOMM Workshop 5G-MeMU*, 2022, pp. 29–35.

[21] A. Baltaci and e. a. Cech, Hendrik, “Analyzing real-time video delivery over cellular networks for remote piloting aerial vehicles,” in *Proc. of ACM IMC*, 2022, p. 98–112.

[22] “Speedtest by Ookla,” https://www.speedtest.net/, 2024, accessed on Jan 12, 2024.

[23] nPerf, “5G coverage map worldwide,” accessed on Jan 12, 2024. [Online]. Available: https://www.nperf.com/en/map/5g

[24] P. Taylor, “Largest US cell phone companies market share 2022,” Nov 2022. [Online]. Available: https://www.statista.com/statistics/199359/market-share-of-wireless-carriers-in-the-us-by-subscriptions/

[25] J. Davies, “Infographic: Who are the MNO market share leaders in europe?” Jul 2017. [Online]. Available: https://telecoms.com/483122/infographic-who-are-the-mno-market-share-leaders-in-europe/

[26] Google, “Cloud computing services,” Apr 2007. [Online]. Available: https://cloud.google.com

[27] Azure, “Cloud computing services,” Feb 2010. [Online]. Available: https://azure.microsoft.com/en-us/

[28] “Amazon web services (aws).” [Online]. Available: https://aws.amazon.com/

[29] S. S. Krishnan and R. K. Sitaraman, “Video stream quality impacts viewer behavior: inferring causality using quasi-experimental designs,” *IEEE/ACM Transactions on Networking*, vol. 21, no. 6, pp. 2001–2014, 2013.

[30] S. Lederer, “Optimal adaptive streaming formats mpeg-dash & hls segment length,” Apr 2020. [Online]. Available: https://bitmovin.com/mpeg-dash-hls-segment-length/

[31] Dash.js, “Dash-industry-forum, dash.js,” accessed on Jan 12, 2024. [Online]. Available: https://github.com/Dash-Industry-Forum/dash.js

[32] K. Spiteri, R. Urgaonkar, and R. K. Sitaraman, “Bola: Near-optimal bitrate adaptation for online videos,” *IEEE/ACM Transactions On Networking*, vol. 28, no. 4, pp. 1698–1711, 2020.

[33] Z. Li, X. Zhu, J. Gahm, R. Pan, H. Hu, A. C. Begen, and D. Oran, “Probe and adapt: Rate adaptation for http video streaming at scale,” *IEEE Journal on Selected Areas in Communications*, vol. 32, no. 4, pp. 719–733, 2014.

[34] C. Johnson, *5G New Radio in Bullets*, 1st ed. Independently published, Jul 2019.

[35] E. P. News, “Roam like at home: roaming rules extended for 10 more years,” accessed on Jan 12, 2024. [Online]. Available: https://www.europarl.europa.eu/news/en/headlines/society/20211015STO15005/roam-like-at-home-roaming-rules-extended-for-10-more-years

[36] nitefood, “Github - nitefood/asn: Asn / rpki validity / bgp stats / ipv4v6 / prefix / url / aspath / organization / ip reputation / ip geolocation / ip fingerprinting / network recon / lookup api server / web traceroute server.” [Online]. Available: https://github.com/nitefood/asn

[37] E. Ramadan, A. Narayanan, U. K. Dayalan, R. A. K. Fezeu, F. Qian, and Z.-L. Zhang, “Case for 5G-aware video streaming applications,” in *Proceedings of the 5G-MeMU*, 2021, p. 27–34.

[38] M. Rochman, V. Sathya, and et al., “A comparison study of cellular deployments in chicago and miami using apps on smartphones,” in *Proc. of ACM WiNTECH*, 2022, p. 61–68.

[39] A. Narayanan, M. I. Rochman, A. Hassan, and et al., “A comparative measurement study of commercial 5G mmWave deployments,” in *Proc. of IEEE INFOCOM*, 2022, pp. 800–809.

[40] A. Hassan, A. Narayanan, A. Zhang, W. Ye, R. Zhu, S. Jin, J. Carpenter, Z. M. Mao, F. Qian, and Z.-L. Zhang, “Vivisecting mobility management in 5G cellular networks,” in *Proc. of ACM SIGCOMM*, 2022, p. 86–100.

[41] Y. Liu and C. Peng, “A close look at 5G in the wild: Unrealized potentials and implications,” in *Proc. of IEEE INFOCOM*, 2023, pp. 1–10.

[42] W. Ye, J. Carpenter, Z. Zhang, R. A. Fezeu, F. Qian, and Z.-L. Zhang, “A closer look at stand-alone 5g deployments from the ue perspective,” in *2023 IEEE International Mediterranean Conference on Communications and Networking (MeditCom)*. IEEE, 2023, pp. 86–91.

[43] Y. Li, C. Peng, Z. Zhang, Z. Tan, H. Deng, J. Zhao, Q. Li, Y. Guo, K. Ling, B. Ding, H. Li, and S. Lu, “Experience: A five-year retrospective of mobileinsight,” in *Proc. of the ACM MobiCom*, 2021, p. 28–41.

[44] O. Alay, A. Lutu, R. García, and et al., “MONROE, a distributed platform to measure and assess mobile broadband networks: Demo,” in *Proc. ACM WiNTECH*, 2016, p. 85–86.