Spectrum & RAN Sharing: A Measurement-based Case Study of Commercial 5G Networks in Spain

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***Abstract*—Radio Access Network (RAN) sharing, which often also includes spectrum sharing, is a strategic cooperative agreement among two or more mobile operators in which one operator may use another's RAN infrastructure to provide mobile services to its users. By mutually sharing physical sites, radio elements, licensed spectrum, and other parts of the RAN infrastructure, participating operators can significantly reduce the capital (and operational) expenditure in deploying and operating cellular networks, while accelerating coverage expansion – thereby addressing the spectrum scarcity and infrastructure cost challenges in the 5G era and beyond. While the economic benefits of RAN sharing are well understood, the impact of such resource pooling on user-perceived performance remains underexplored, especially in real-world commercial deployments. We present, to the best of our knowledge, the first empirical measurement study of commercial 5G spectrum and RAN sharing. Our measurement study is unique in that, beyond identifying real-world instances of shared 5G spectrum and RAN deployment "in the wild", we also analyze users' perceived performance and its implication on Quality of Experience (QoE). Our study provides critical insights into resource management (*i.e.,* pooling) and spectrum efficiency, offering a blueprint (and implications) for network evolution in 5G, 6G, and beyond.**

***Index Terms*—5G NR, RAN sharing, spectrum sharing, measurements, QoE.**

I. INTRODUCTION

Radio spectrum and radio access network (RAN) infrastructure are two major expenses in cellular network deployment and operations. According to [1], since 2000, telecommunications operators have incurred approximately $1 trillion in spectrum access costs, including up to 45% paid upfront through primary license awards, $50–100 billion for clearing and refarming, and the remainder in recurring spectrum license fees. Likewise, based on the 2024 key industry statistics [2], Wireless Infrastructure Association (WIA) estimates that in 2024 alone, the U.S. cellular industry invested over $10.8 billion in deploying new and upgraded networks, with $8.4 billion dedicated to the RAN.

To partly lower and share the cost burdens, 3GPP has introduced the concept of *network sharing* in its Specification TS 23.251 [3], which allows multiple network operators to share radio access elements (*RAN sharing*), which may also include the sharing of the radio resources themselves (*spectrum sharing*). The main type of network sharing is Multi Operator Core Network (MOCN), in which multiple mobile operators, each with their own dedicated core network, share certain radio access elements (e.g., base stations) at specific locations. RAN sharing and spectrum sharing (as part of RAN sharing) are in particular deemed as important mechanisms in 5G deployment to share spectrum, improve coverage, and reduce costs [4]. In 2024, indirect network sharing (INS) was introduced in 3GPP 5G-Advanced Release 20 as the next step in network sharing evolution [5] (see §II for more details).

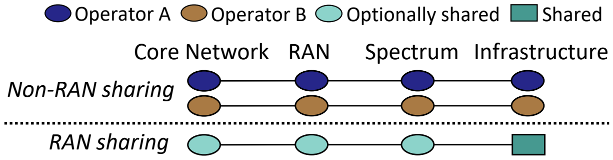

Fig. 1. Shared and non-shared Network Elements in RAN Sharing.

At first glance, network sharing may sound similar to the situation of Mobile Virtual Network Operations (MVNO) [6], where an MVNO leases network access from an MNO (Mobile Network Operator) to offer/resell mobile services without owning the physical infrastructure – hence in a sense the MVNO "shares" the physical infrastructure of the MNO. Network sharing, as defined by 3GPP, however, refers specifically to the cases where multiple MNOs share parts of their network infrastructure (see Fig. 1 for an example). Hence, it also differs from *roaming*, where a "foreign" (visited) MNO provides temporary mobile access to a visiting user from another MNO. In a nutshell, the goal of network sharing is to allow multiple MNOs to share part of their network infrastructure to reduce costs and improve coverage.

With the rollout of 5G networks (and enormous associated costs) since 2019, several RAN sharing agreements between MNOs have been publicly announced in multiple countries (see, e.g., [7]–[9]). Several white papers/research papers [10]–[13] have also been published that analyze the potential economic benefits of RAN sharing. For instance, SoftBank and KDDI in Japan both claimed [8] that by sharing 4G base station infrastructures, they are able to cut capital expenditure by about $288 million for each company, with (part of the) cost savings often passed down to customers

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through lower service prices. Beyond cost savings, RAN sharing can also offer performance benefits for users, as suggested by several simulation-based studies [14], [15]. While the notion of RAN sharing has been introduced by 3GPP for some time and 5G networks have been rapidly rolled out since 2019, there have been no *publicly available* research studies that identify the existence of RAN sharing in *real world 5G deployment*, not to mention quantifying the performance impacts of RAN sharing on mobile applications from a user's perspective. This paper aims to fill this gap.

We have conducted an extensive measurement study of commercial 5G network deployment in Spain. Our study provides the first measurement-based, quantitative evidence of 5G network sharing "in the wild" in Spain, where two operators, Vodafone and Orange, not only share the RAN infrastructure but also spectrum (an n78 channel owned by Vodafone). This finding is further supported by the Spanish government's spectrum auction data, as well as the public announcement of a network-sharing agreement between the two operators [7]. With the discovery of RAN (and spectrum) sharing in a real-world deployment scenario, we further investigate the following questions: 1) How do commercial spectrum and RAN sharing impact resource management in the 5G era? 2) Under RAN sharing, do both operators benefit equally in terms of performance? 3) Does an operator deliver similar performance to its users with and without RAN sharing? 4) Does the resource pooling enabled by RAN and spectrum sharing translate into improved QoE for users? We summarize the main contributions of our measurement-based inquiry of RAN and spectrum sharing below.

- We advance commercial 5G understanding and conduct – to the best of our knowledge, the first large-scale, comprehensive, and comparative measurement study of commercial 5G spectrum and RAN sharing in Spain, filling an important gap in the existing 5G measurement literature [1].
- Through our detailed measurement analysis, we analyze RAN sharing and non-RAN sharing performance characteristics, and further quantify their direct effects on application QoE.
- Our measurement provides insights into deployment strategies, the intricacies of resource pooling in RAN sharing, and their implications for 5G evolution.

While our study presents a *real-world* case study of RAN and spectrum sharing in Spain, we believe that both the measurement methodology we have developed and the findings and insights we have obtained will be widely applicable in other countries and scenarios. The mobile industry and the 3GPP standard organization are now in the midst of 6G radio and network architecture and technology specifications. With increasing demand and costs for spectrum [16], it is widely believed that (dynamic) spectrum sharing will be a key feature among many others under study. The costs of deploying new 6G radio elements or upgrading the existing 5G RAN infrastructure to future 6G standards, however, are a major hurdle for Mobile Network Operator (MNO)s to fully embrace 6G [17]. Spectrum and RAN sharing – and, more broadly, network sharing – will therefore play a critical role in reducing costs, expanding coverage, improving performance, and enhancing user experience, thereby benefiting both operators and end users.

II. BACKGROUND & MOTIVATION

In this section, we present the technical background and introduce key concepts and terminology related to RAN sharing, including both passive and active RAN sharing architectures. We then discuss the motivation and key research questions that guide our work.

A. Spectrum and RAN Sharing Background

In the traditional single-operator ownership model, an operator is fully responsible for: (i) acquiring spectrum, typically through regulated auctions or other mechanisms such as mergers, acquisitions, or geographic/short-term leasing—an expense that represents one of the largest costs in cellular network deployment; (ii) deploying, operating, and maintaining its own infrastructure, including sites, towers, backhaul, spectrum, the RAN, and the core network, thereby incurring significant capital and operational expenditures; and (iii) provisioning and managing services, as well as handling subscriber billing, charging, and accounting functions [18]. In the spectrum and RAN sharing model, two or more operators jointly deploy, operate, and maintain the network[2]. Operators may share different parts of the network, including infrastructure, spectrum, RAN, and even part of the core network, while remaining independent [19]. For the network subscriber, the services appear normal without interruptions.

The motivation for Spectrum/RAN sharing is to reduce cost while enhancing network capacity. RAN sharing was widely adopted through successful transitions between mobile network generations (*i.e.,* 2G→3G and 3G→ 4G), only to reduce the investment cost required for these technology migrations. In the case of 5G with ultra-high throughput requirements, RAN sharing is not just about reducing costs but primarily about addressing spectrum scarcity. Several RAN sharing architectures have been discussed in the industry and have been standardized within 3GPP [19]. Based on which network elements the operators agree to share, there are two main types of sharing: passive and active RAN sharing. Table I summarizes the main RAN sharing architectures.

Passive RAN sharing: This is also known as infrastructure sharing according to 3GPP TS 32.130 [19]. In this type of sharing, only the physical site and civil infrastructure (like the towers, rooftop space, equipment shelters, backup power (batteries, generators), cooling/air conditioning, grounding, and cabling trays) are shared. The operators retain independent spectrum, RAN, and core network infrastructures.

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[1] A curated dataset specifically prepared for the artifacts of this study will be made available upon request. A large dataset that includes the measurement studies we conducted in Madrid, Spain, is available at https://github.com/SIGCOMM24-5GinMidBands/artifacts.

[2] 3GPP allows RAN sharing among up to six operators [19].

TABLE I
COMPARISON OF RAN SHARING ARCHITECTURES.

Type of Sharing	Scenario	What is Shared	Key Characteristics
Passive RAN Sharing		Civil infrastructure only, *i.e.,* Sites, towers, masts, power, cooling, backhaul *etc.*	Cost-driven model; no sharing of radio equipment, spectrum, or RAN functions.
Active RAN Sharing	MORAN	Infrastructure + RAN nodes (*e.g.,* NodeB, eNB, gNB), antennas, radio equipment	Active RAN sharing while retaining independent spectrum ownership.
	MOCN	Infrastructure + RAN + Spectrum resources	Widely deployed active sharing model. Improves spectrum utilization & cost efficiency.
	GWCN	Infrastructure + RAN + spectrum resources + part (or all) of core network	Greater cost savings but reduces flexibility and roaming support.
	INS	Infrastructure + RAN Traffic routed via a "master" operator core network	Operational arrangement similar to roaming but within a sharing agreement.

Active RAN sharing: Here, different network elements are shared and can be organized as follows:

1) Multi-Operator Radio Access Network (MORAN): In MORAN, the infrastructure and RAN are shared. Spectrum and core network resources are not pooled. As a result, operators with a large spectrum will benefit from high capacity [20]. This is an industry RAN sharing, not defined by 3GPP.

2) Multiple Operator Core Network (MOCN): Here, not only the infrastructure and RAN are shared, but also the spectrum. However, operators maintain separate core networks [5], [21]. In this RAN sharing scenario, spectrum resources scheduling is done fairly across users belonging to different operator [20]. Unlike MORAN, this type of RAN sharing is defined by 3GPP.

3) Gateway Core Network (GWCN): In this 3GPP sharing architecture, in addition to the infrastructure, spectrum, and the RAN, part or all of the core network is also shared [21]. This provides greater cost savings at the expense of reduced flexibility, especially in mobility scenarios involving multiple control-plane network functions.

4) Indirect Network Sharing (INS): Infrastructure and RAN are shared. Participating operators do not have direct connections to the shared RAN. Communication between the shared RAN and the core network of the participating operators is routed via the core network of the master operator, similar to roaming with joint RAN operations.

B. 5G Background and Motivation

Brief 5G Background: In 5G networks, when a User Equipment (UE) initiates voice or data communication, it must first establish a connection with the base station. The UE utilizes the operator's allocated spectrum, which determines the available Physical Resource Block (PRB) during scheduling–where a physical resource block is the fundamental unit of radio resource allocation [22]. To access the core network, the UE must also undergo a series of control-plane operations [23]. A key procedure among these is the Radio Resource Control (RRC) connection process, which transitions the UE from the *RRC_IDLE* state to the *RRC_CONNECTED* state. The UE must be in the *RRC_CONNECTED* state before it can transmit or receive user data. During this process, another critical connection establishment procedure is triggered: the Packet Data Network (PDN) connection procedure in 4G LTE or the Packet Data Unit (PDU) session establishment in 5G. These procedures provide end-to-end (E2E) user-plane connectivity from the UE, through the RAN, to the core network. Consequently, depending on which components are shared, the performance experienced by users—both in terms of latency and throughput—may vary, as we show later in §IV.

Motivation: Consider a scenario in which two operators, in addition to sharing infrastructure and spectrum, (i) *share the RAN* or (ii) *share part or all of the core network*. In case (i), users' voice and data traffic must be routed to their respective core networks, whereas in case (ii), traffic is directed to a shared core network. This setup raises important questions about mobility management, particularly how user connections to the RAN are handled as users move across coverage areas. Specifically, what is the impact of sharing part or all of the RAN and/or core network on Handovers (HOs)–the key mobility management procedure through which a UE's ongoing session is transferred to a new base station (BS) with better signal quality [24]? These considerations raise several important—and largely unanswered—questions: (1) *How does control-plane latency under RAN sharing compare to that in non-sharing deployments?* (2) *Does resource pooling enabled by RAN sharing lead to improved data-plane performance for users?* (3) *How does RAN and/or core sharing impact user QoE?*

III. SPECTRUM ACQUISITION IN SPAIN AND MEASUREMENT METHODOLOGY

In this section, we begin by examining spectrum acquisition in Spain, contrasting publicly available information on spectrum auction outcomes with insights derived from our measurement data. We highlight the complexities of operator agreements and spectrum exchanges that are not fully captured in public records. Using our measurement data, we identify evidence of active RAN sharing between Orange and Vodafone in Spain. We conclude with a detailed description of our data collection methodology.

A. Spectrum Acquisition in Spain

Although 3GPP specifies "allowable" channel bandwidths for each 5G band[3], the bandwidth deployed in practice is largely determined by the spectrum acquired by each operator through auctions, mergers, or other acquisition mechanisms. This distinction has direct implications for RAN sharing, as the effective channel bandwidth depends on both spectrum holdings and the sharing arrangements between participating operators. It is important to note that spectrum acquisition is one of the largest cost components in 5G deployments. In this work, we use the Spanish telecommunications market as a case study to analyze how regulatory outcomes translate into operational network deployments.

Auction Outcomes: From public sources, the Spanish spectrum authority assigned the n78 band (3.4 – 3.8 GHz) via three separate auctions. (i) 2016 Auction (3.4 – 3.6 GHz) [25]: After this auction, MasMovil (now part of Yogio Spain) secured 80 MHz in two non-contiguous 40 MHz channel/spectrum blocks; 3.4 – 3.44 GHz and 3.5 – 3.54 GHz. Telefonica and Orange each acquired 40 MHz, split into 20 MHz segments. (ii) 2018 Auction (3.6 – 3.8 GHz) [26]: In this phase, Vodafone Spain spent 198.1 million euros to acquire eighteen 5 MHz blocks for a total of 90 MHz and Orange Spain spent 132.2 million euros and obtained 60 MHz (twelve 5 MHz channels), while Telefonica spent 107.4 million euros to purchased a 50 MHz (ten 5 MHz) channel bandwidth. (iii) In 2021 [27], Telefonica and Orange each further bid and purchased two 10 MHz channels[4]. The remaining 3.48 – 3.5 GHz channels were acquired by Yogio Spain. In summary, after the n78 band auctions, Orange was allocated 110 MHz, Telefonica 100 MHz, Vodafone 90 MHz, and Yogio 80 MHz.

"In the Wild" Observation: From the above auction outcomes, Orange and Telefonica in Spain both own non-contiguous, scattered channel bandwidths, which require Carrier Aggregation (CA) to increase data rates [29]. However, measurement data reveals that Orange is now operating a contiguous 100 MHz channel (3.6 – 3.71 GHz) – a block that overlaps with Telefonica's 2018 acquisition. This observation suggests a post-auction spectrum swap between Orange and Telefonica to make their spectrum contiguous. We later confirmed this by [28], which indicates that Telefonica now controls a contiguous 100 MHz (3.5 – 3.6 GHz) channel.

Spectrum and Active RAN Sharing: Interestingly, based on our measurement, both Orange and Vodafone use the exact same 90 MHz channel (3.71 – 3.8 GHz). While Vodafone remains the sole legal owner of this specific block [28], Orange Spain utilizes it via a spectrum and RAN infrastructure sharing (and part of the core network) agreement with Vodafone Spain [11]. As a result, Orange is able to extend its 5G footprint by leveraging Vodafone's spectrum and RAN infrastructure in specific geographic areas. This active spectrum and RAN sharing represents a commercial deployment of the RAN sharing specified by 3GPP [3]. Next, we present a detailed discussion of our measurement methodology and data collection process.

B. Measurement Methodology & Data Collection

Our RAN Sharing study and analysis is made possible by carefully orchestrating data collection that focuses on three dimensions: (1) *5G operators*, (2) *measurement platform and applications*, and (3) *orchestration of data collection.*[5]

5G Operators: We relied on public information available on the Internet to identify countries with operators that have come to a spectrum/RAN sharing agreement. We identified Orange and Vodafone in Spain [11], and also confirmed this using our measurement data as mentioned earlier. We next relied on several related works like [31], [32], and platforms like nperf [33] and Ookla speedtest [34] to identify cities in Spain where Orange and Vodafone have deployed 5G services. Both Orange and Vodafone deploy their 5G services in 5G mid-band, *i.e.,* 3.3–3.8 GHz, in band n78. We purchased four contract SIM cards (two per operator) to avoid performance throttling.

Measurement Platform and Applications: Since our goal is to study spectrum/RAN sharing performance from both the network (*i.e.,* PHY and MAC layers) and user (application) perspective, we carefully designed a comprehensive measurement platform. We selected a diverse set of testing servers and applications. We leveraged Ookla speedtest servers deployed within/close to Orange and Vodafone's networks in Madrid, Seville, Barcelona, Bilbao, and Valencia to measure and compare the E2E latency and the "raw" downlink (DL) and uplink (UL) throughput under RAN-sharing and non-RAN-sharing. We additionally conducted `iPerf`, ping, and traceroute experiments using cloud servers. We deployed cloud servers in Google Cloud Platform (GCP), Microsoft Azure Cloud, and Amazon AWS Cloud, the three major cloud service providers. To study the impact of spectrum/RAN sharing on users' application QoE, we also designed and conducted video streaming experiments.

Unlike in-lab experiments conducted in a controlled environment, conducting experiments in the wild poses several challenges. Therefore, we deployed automated custom scripts to ensure reliable data collection (to the extent possible). Since the phone's capabilities have been shown to affect user performance [22], [29], we use four identical Samsung Galaxy S21 Ultra phones for all our experiments. To extract measurements across the 5G network– *i.e.,* 5G New Radio (NR) – we use Accuver XCAL [35], a professional cellular measurement tool. The smartphones are connected via USB-C

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[3] For example, for the n78 band, the specified channel bandwidths are 10, 15, 20, 25, 30, 40, 50, 60, 70, 80, 90, and 100 MHz.

[4] In the first auction in 2016, the Spanish spectrum authority reserved two 20 MHz channels in the 3.4 – 3.6 GHz range for military radio service. Telefonica's 20 MHz acquisition in the third auction is likely those reserved, according to [28].

[5] A detailed discussion of our measurement campaign is outlined in our recently published paper [22]. Refer to [30] for a focused measurement discussion of our Roaming study. Here, we provide a discussion of our measurement campaign focused on RAN sharing in Spain. We emphasize that this research was conducted independently; no proprietary data was provided by Orange or Vodafone, and no authors are affiliated with these entities.

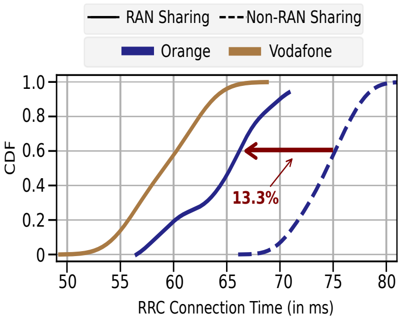

Fig. 2. RRC Connection Time with and without RAN Sharing.

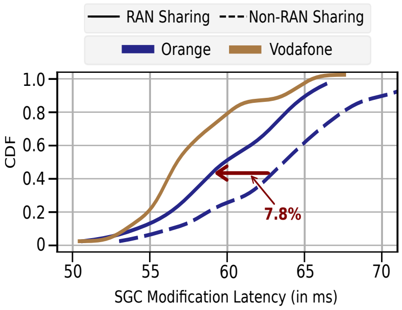

Fig. 3. SGC Modification Latency with and without RAN Sharing.

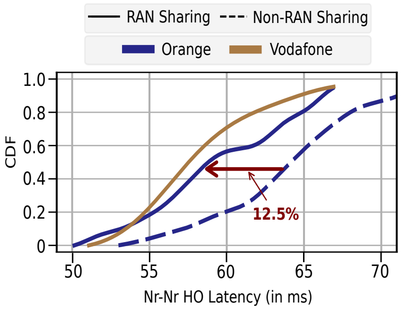

Fig. 4. NR-NR HO Latency with and without RAN Sharing.

to a Windows laptop running XCAL. XCAL supports up to six devices simultaneously and enables concurrent data collection across the full 5G NR protocol stack, with data extracted directly from the 5G modem chipsets. We conducted both stationary and drive-test experiments.

Data Collection: Using our measurement platform, we conducted an extensive 5G RAN sharing measurement campaign. For data collection, we performed drive tests across Madrid, running downlink `iPerf` experiments to identify 5G areas where Orange and Vodafone operate using shared 5G spectrum under their agreement [11]. We identified two such areas around Madrid. Subject to financial constraints, we conducted both stationary and drive-test experiments and collected detailed measurements for RAN-sharing and non-RAN-sharing scenarios in Madrid, Spain, across different weekdays and weekends. In summary, we collected more than 1,060 minutes of non-RAN sharing measurements and over 1,100 minutes of RAN sharing measurements across 5G networks, totaling more than 1.2 TB of data.

IV. PERFORMANCE ANALYSIS OF RAN SHARING

In this section, we use our measurement data to compare the performance under RAN-sharing and non-RAN-sharing scenarios. Specifically, we compare the control-plane latency and throughput for RAN-sharing and non-RAN-sharing between Orange and Vodafone in Spain. We conclude by examining how the "raw" throughput performance impacts user experience, an aspect that, to the best of our knowledge, remains underexplored in 5G systems.

A. RAN Sharing Impact on Control Plane Latency

We quantitatively study the control plane latency with and without RAN sharing. Recall from §II-B that, when a UE needs to send/receive voice/data over the cellular network, it must transition into the *RRC_CONNECTED* state. This process entails establishing a data PDN/PDU session with the operator's core network. Here we compare the latency of three key control plane procedures under RAN sharing and non-RAN sharing: **(i)** ***RRC Connection Time:*** The time elapsed for a UE to transition from an *RRC_IDLE* state to an *RRC_CONNECTED* state to send/receive voice/data. This procedure includes the time required to establish a PDN/PDU connection with the core. **(ii)** ***Secondary Cell Group (SCG) Modification Latency:*** The delay incurred when changing the secondary base station group connected to the UE while maintaining the primary cell connection. **(iii)** ***NR-NR Handover (HO) Latency:*** The delay to redirect a UE's voice and data to a new base station with better signal quality.

We study the control-plane latency performance when an Orange UE connects to its home network, Orange – *i.e.,* non-RAN sharing, and when the same Orange UE connects to Vodafone – *i.e.,* RAN sharing. Fig. 2 shows the *RRC Connection Time* for Orange subscriber under RAN sharing and non-RAN sharing. We observe that the *RRC Connection Time* drops (*i.e.,* improves) by 13.3% with RAN sharing. We also find that the modification of secondary cell groups (SCG latency) using RAN sharing also drops (improves) by 7.8%, as illustrated in Fig. 3. These findings indicate that non-shared cells are also added to a UE cell group. Additionally, we quantify the *NR–NR HO latency* of the Orange UE while driving using RAN sharing and non-RAN sharing, as shown in Fig. 4. We observe a 12.5% drop (*i.e.,* improvement) in control-plane latency for Orange under RAN sharing compared to non-RAN sharing.

When we compare a Vodafone user with an Orange user, under RAN sharing, we observe that the *RRC Connection Time* and *SCG latency* are 8.03% and 4.71% lower (*i.e.,* better) for Vodafone users (see Fig. 2 and Fig. 3). However, these differences are smaller when we compare the Vodafone user with the baseline non-RAN sharing Orange performance. Although not explicitly shown in the figures, we observe that Vodafone users exhibit the same control-plane latency performance under RAN sharing as in the non–RAN-sharing case. In other words, Vodafone users maintain consistent control-plane latency QoE, even when actively sharing the RAN with Orange users.

These results imply that Orange and Vodafone in Spain also share part of the core network. We further confirm this by extracting the Mobility Management Entity (MME) code, which is 232 in our study. The MME code includes the Access and Mobility Management function (AMF) identifier (a core network function) to which the UE is connected. Since the MME code is identical in both RAN-sharing and non-RAN-sharing scenarios, Orange and Vodafone are likely sharing part of the core network. We note that AMF sharing may introduce potential security concerns, which remain to

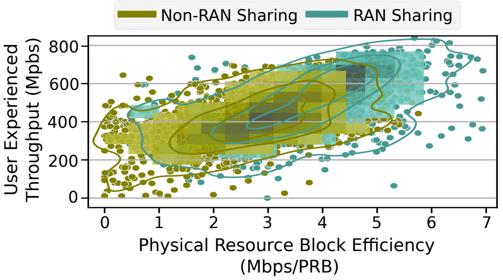

Fig. 5. [Orange] PRB Efficiency and UE Throughput under RAN-Sharing and non–RAN-Sharing Scenarios.

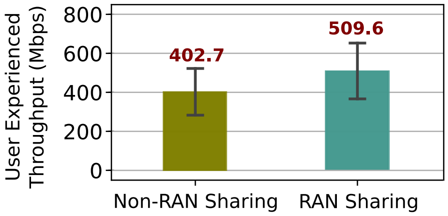

Fig. 7. Comparison of Orange Subscriber UE Throughput under non–RAN-Sharing and RAN-Sharing Scenarios.

be investigated. The reduced control plane latency resulting from sharing part of the core network is consistent with the behavior expected under GWCN active RAN sharing. Since our analysis is based on UE-side measurements, this observation provides indirect evidence rather than definitive confirmation of the underlying network architecture. Overall, our results highlight the benefits of resource pooling under RAN sharing, particularly in reducing control-plane delay. Next, we quantitatively analyze data-plane performance.

B. RAN Sharing Impact on Throughput

To understand how RAN sharing affects user performance, we quantify throughput in RAN-sharing and non-RAN-sharing scenarios. Fig. 7 shows the UE downlink throughput (y-axis) for the non–RAN sharing and RAN sharing cases. We observe a 26.55% increase in throughput, from 402.7 Mbps to 509.6 Mbps, when the UE operates under RAN sharing compared to non–RAN sharing.

To further analyze resource utilization, we quantify the PRB efficiency – a measure of how effectively the network utilizes PRBs – in RAN-sharing and non–RAN-sharing scenarios. Fig. 5 shows a scatter plot of the PRB efficiency (Mbps/PRB) on the x-axis and UE throughput on the y-axis. We observe that the network achieves higher PRB efficiency under RAN sharing. We suspect that this gain is primarily due to resource pooling, which is known to optimize PRB allocation [36]. For instance, as shown in Fig. 6, when pooling resources, operators can implement and utilize higher Modulation and Coding Scheme (MCS) values (x-axis), which in turn increases the amount of data sent on the wireless link (*i.e.,* Transport Blocks Size) (y-axis), and consequently increases the throughput. Additionally, in RAN sharing deployments, operators can mitigate redundant control-plane messages and procedures and optimize the HO process – as also demonstrated in Fig. 4 – thereby freeing up additional resource blocks. This allows more user data to be multiplexed, resulting in higher PRB efficiency and, consequently, increased throughput. Such performance gains highlight the benefits of RAN sharing in mobile networks, particularly for 5G/NextG applications that require ultra-high throughput.

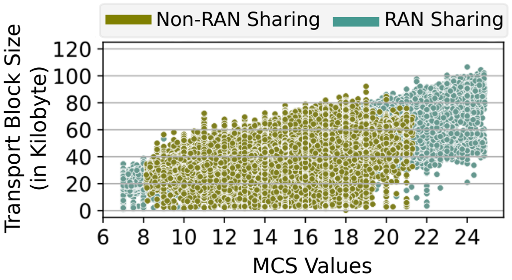

Fig. 6. [Orange] Transport Block Size (TBs) and MCS under RAN-Sharing and non–RAN-Sharing Scenarios.

C. RAN Sharing Impact on Application QoE

Our objective is to quantitatively evaluate the impact of RAN sharing on user-perceived QoE. We conducted video streaming experiments in both RAN-sharing and non–RAN–sharing scenarios.

Experiment Approach: In these experiments, a UE streams a video by downloading video chunks from a remote server located in the same geographical area as the UE (both are in Madrid, Spain). The video is segmented into fixed-length 4-second chunks, consistent with the recommended chunk duration for Adaptive Bitrate (ABR) streaming [37], and encoded at multiple quality levels. Using FFmpeg with the libx264 codec, we encode a 210-second video into seven bitrate levels at 30 frames per second (fps). The seven quality levels correspond to approximate bitrates of 30 Mbps, 60 Mbps, 75 Mbps, 200 Mbps, 400 Mbps, 600 Mbps, and 750 Mbps. As throughput varies over time in both RAN-sharing and non–RAN-sharing scenarios, the ABR algorithms dynamically adapt the requested video chunk quality to improve QoE. For our implementation, we used DASH.js [38], a popular open-source video streaming framework, and deployed two ABR algorithms: BOLA [39] and a dynamic bitrate algorithm. We used a custom HTML-based player to conduct trace-based emulation under both RAN-sharing and non–RAN–sharing conditions. For our analysis, we normalized the stall time percentage (*i.e.,* the fraction of time elapsed while waiting for a video chunk to be played) and the average bitrate of the delivered video chunks.

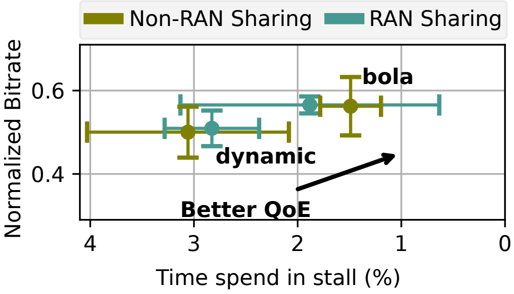

Fig. 8. [Orange] QoE Performance under RAN Sharing and Non-RAN Sharing.

Fig. 8 presents the normalized average bitrate (y-axis) and stall time percentage (x-axis) for video streaming in the RAN-sharing and non–RAN–sharing scenarios. We observe a slight increase in bitrate in the RAN sharing scenario, regardless of the ABR algorithm, consistent with the slight increase in the throughput observed earlier under RAN sharing. These results suggest that current ABR algorithms play a limited role in improving UE QoE in the RAN sharing scenario. A more detailed analysis of the dynamics of specific ABR algorithms during streaming, particularly the differences in stall time performance between RAN-sharing and non–RAN–sharing scenarios, is left for future work. Nonetheless, our analysis provides insight into how RAN sharing can improve QoE.

V. RELATED WORK

We organize the related work on RAN sharing into three categories: (i) studies examining the theoretical economic and technical potential of RAN sharing; (ii) analyses of other commercially deployed forms of operator collaboration, such as MVNO arrangements and roaming, which are frequently discussed in the literature and sometimes conflated with RAN sharing; and (iii) experimental academic studies on RAN sharing. We conclude this section by articulating the research gap our work addresses and clarifying how it advances the understanding of commercial 5G deployments.

A. Economic and Technical Potential of RAN Sharing

Several RAN sharing deployments have been implemented by commercial mobile networks worldwide [7], [8], [10]. Studies conducted in [11]–[13] show that active RAN sharing significantly enhances both network quality and market competition. Koutroumpis *et al.* [13] analyzed the economic and technical outcomes of RAN sharing using an extensive real-world dataset covering 140 mobile operators across 29 European countries over a 20-year period (2000–2019). These studies indicate that sharing leads to faster technology rollouts (4G/5G), broader coverage, and increased download speeds. Furthermore, these technical gains do not come at the cost of competition; instead, the operational savings are often passed down to consumers, resulting in lower service prices. While passive RAN sharing provides cost relief to operators, active RAN sharing is the clear driver for superior technical performance, enabling smaller operators to provide service quality comparable to that of larger operators.

B. Mobile Virtual Network Operators & Roaming

In addition to RAN sharing, operators use other collaborative service models to reduce costs, such as *roaming* and *Mobile Virtual Network Operator (MVNO)*. *Roaming* is a widely adopted service-level agreement that ensures service continuity when users are outside their home network's coverage. Visited network provides radio access; authentication and billing are anchored in the home network. Most mobile operators maintain such agreements, aiming to expand network coverage; however, most roaming agreements impose limits on the maximum data volume and service speed available to roaming users, which can negatively affect the resulting QoE [40]. *MVNO* is a commercial/wholesale agreement that enables a mobile network to operate without deploying full infrastructure, but instead leases network capacity from a host operator to provide retail services under its own brand. An MVNO is identified by its operation without ownership of licensed spectrum, obtaining access through agreements with a licensed operator [41]. Unlike RAN sharing architectures, roaming and MVNO arrangements involve collaboration at the service and business levels, while the network infrastructure remains owned and managed independently by each operator.

C. Academic RAN Sharing Studies

Most existing studies on RAN sharing rely on simulation data or experimental laboratory networks [14], [15], while only a limited number examine performance in commercial (live) mobile networks from a user perspective. Türk and Zeydan [42] show that active RAN sharing can effectively enhance network capacity and user experience without degrading core network performance. They conducted an experimental RAN sharing trial on live 4G networks in Turkey. They enabled RAN sharing at operational sites and systematically compared performance metrics before and after the sharing configuration to quantify the impact of sharing on throughput and mobility performance.

Research Gap: While the related work discussed above advances our understanding of RAN sharing—from "theoretical and laboratory-based analyses", to alternative cost-reduction service models adopted by operators, and Türk and Zeydan's study of RAN sharing in 4G–it remains limited in several key aspects. In particular, prior work does not fully address: (i) whether the "theoretical" economic and performance gains envisioned for RAN sharing translate to real-world commercial deployments; (ii) how effectively RAN sharing operates in the 5G era; and (iii) how RAN sharing impacts user experience in 5G networks. Our work directly addresses these gaps and contributes to the understanding of commercial 5G networks under spectrum and RAN sharing.

VI. CONCLUDING REMARKS

In this paper, we present, to the best of our knowledge, the first measurement-based, quantitative analysis of 5G network sharing "in the wild". Through a comprehensive measurement campaign in Spain and detailed analysis, we investigate how commercial spectrum and RAN sharing impact user performance in the 5G era. Specifically, we quantify the performance implications of RAN sharing between Orange and Vodafone in Spain and evaluate how resource pooling translates into QoE improvements. Our analysis shows that participating operators benefit comparably in terms of throughput under RAN sharing; however, these gains do not always translate into improved QoE for users. For one operator (Orange in this study), its subscribers' performance improves significantly under RAN sharing (*i.e.,* when leveraging

Vodafone's spectrum and RAN infrastructure) compared to non-RAN-sharing scenarios. Importantly, Vodafone users are not adversely affected in terms of performance when sharing resources with Orange users. While our study focuses on RAN sharing in Spain, we believe that our findings generalize to other countries and deployment scenarios, particularly in the context of emerging 6G systems, where (dynamic) spectrum and RAN sharing are expected to play a central role.

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