A Longitudinal Study of 5G NSA/SA Infrastructure and User Adoption from an MNO Perspective

Antonio Boiano$^{◇†}$, Máximo Pirri$^{◇*§}$, Diego Madariaga*, Nadezda Chukhno*, Cezary Ziemlicki‡,
Zbigniew Smoreda‡, Alessandro Enrico Cesare Redondi†, Marco Fiore*

*IMDEA Networks Institute, Spain, †Politecnico di Milano, Italy, ‡Orange Innovation, France, §University of Alcalá, Spain

{maximo.pirri, diego.madariaga, nadezda.chukhno, marco.fiore}@networks.imdea.org,
{antonio.boiano, alessandroenrico.redondi}@polimi.it, {cezary.ziemlicki, zbigniew.smoreda}@orange.com

Abstract—**The rollout of 5G represents a significant advancement in the telecommunications industry, offering the potential for markedly enhanced speeds, reduced latency, and improved connectivity. Considering these anticipated advantages, it is interesting to understand the progressive adoption of the new technology by operators and their subscribers. In this paper, we analyze the evolution and current operation of the nation-wide 5G network of Orange, a leading mobile operator in France. By inspecting longitudinal data about (*i*) the over-five-year-long development of the country-wide 5G radio access infrastructure and (*ii*) the last two years of 5G traffic demands, we unveil how the operator has planned the deployment of the 5G radio access and characterize the actual usage patterns of the available 5G infrastructure. We also investigate the recent introduction of a 5G Standalone (SA) commercial service and its adoption by the mobile subscribers. We show that by mid 2025, the 5G network under study has achieved substantial coverage of populated areas and the operator has very recently started adding capacity layers to its 5G radio access. However, our investigation reveals that such massive infrastructure deployment efforts are not matched by a commensurate adoption of the technology by the end users, as the 5G capacity –especially for SA– stays largely underutilized.**

I. INTRODUCTION

The evolution of mobile communication technologies has been characterized by a continuous pursuit of enhanced speed, capacity, and connectivity, fundamentally transforming the interaction between individuals, industries, and the digital world [1]. Each Radio Access Technology (RAT) generation, from analog voice calls in 1G to mobile broadband in 4G, has represented a significant leap in mobile service support. The introduction of fifth-generation (5G) mobile networks represents another substantial advancement, promising not merely incremental improvements but a paradigm shift towards a hyper-connected society with diverse new applications, ranging from enhanced mobile broadband to massive Internet of Things (IoT) and critical communication services.

Early 5G rollouts, started in 2019 [2], hinged upon the Non-Standalone (NSA) architecture, which leverages the existing 4G Core Network (CN) to serve the 5G Radio Access Network (RAN) to facilitate the initial release of the new RAT [3]. The second phase of the deployment is associated with the 5G Standalone (SA) paradigm, where an actual 5G CN is established, and 5G capabilities become end-to-end.

Despite the global discourse on 5G potential and worldwide ongoing rollouts, the success of the new technology remains under question. Numerous market analyses provide general estimates of the 5G penetration [4]–[6] and a flurry of measurement studies explore the performance of 5G networks from the standpoint of the end user [7]–[16]. However, those investigations lack the Mobile Network Operator (MNO) perspective that is required to closely monitor the status of the technology and to assess its adoption by the user population. As a result, important facets of the 5G development stay unexplored.

We investigate two of these understudied aspects, *i.e.*, (*i*) the deployment strategy of 5G NSA and SA RATs in a large-scale mobile network and (*ii*) the adoption of the 5G technology by the customer base of the operator. We also break down our analyses across urbanization levels so as to explore differences emerging in urban, suburban, or rural areas. To the best of our knowledge, there is no existing research that characterizes the unfolding of the 5G RAN capacity across a whole country or its evolving utilization over the years. In addition, our research contributes a unique angle –that of an MNO– to the still relatively thin literature on measurements of 5G SA networks.

To provide the contributions above, we study the production network of a major MNO in a European country, *i.e.*, Orange in France. We leverage over five years of radio access planning information and two years of network traffic measurements to reveal the strategy adopted by the operator to progressively deploy 5G coverage and capacity, as well as to comprehend how customers adopt the new technology. Our results unveil several patterns that corroborate the prevailing perception that 5G is still struggling to consolidate its position as a key paradigm for mobile access, even in a developed country like France. Specifically, we show the following.

- Infrastructure development efforts are characterized by a steady expansion of the 5G coverage using mid-band spectrum, reaching the same geographical coverage as 4G in urban regions and providing service to over 90% of the population by 2025. A sudden, large-scale deployment of low-band capacity has recently complemented the RAN.
- The traffic share of 5G has been growing more slowly than the RAN infrastructure and, by mid 2025, the load served by the typical 5G antenna is half that of a co-located 4G antenna, indicating severe under-utilization.

$^◇$These authors contributed equally to this work.

TABLE I: Summary of prior 5G measurement studies compared to ours. View is the vantage point: client (C), service provider (S) or network operator (N). Time is the measurement observation interval, in days (d), weeks (w), months (m) or years (y). Scale is the number of monitored devices or users.

Study	Year	View	Time	Scale	Coverage	4G	NSA	SA
[7]	2020	C	4 m	2-3	city×3	✓	✓	✗
[8]	2020	C	4 m	4	city×3	✓	✓	✗
[17]	2020	C	4 m	5+	site×6	✓	✓	✗
[9]	2021	C	4 m	3–4	city×2	✓	✓	✓
[12]	2022	C	2 d	3-4	city×1	✗	✓	✗
[18]	2022	C	2 d	5+	country	✓	✓	✓
[10]	2022	C	<1 d	5+	city×3	✓	✓	✗
[11]	2022	C	7 w	2	city×1	✓	✓	✗
[13]	2022	C	3 m	5+	city×1	✓	✓	✗
[19]	2023	C	8 d	3	city×1	✗	✓	✗
[20]	2023	C	8 d	5+	country	✓	✓	✗
[21]	2023	C	1 m	100+	city×2	✗	✓	✓
[15]	2023	C	4 m	6	city×5	✓	✓	✗
[14]	2023	C	3 y	5+	city×1	✓	✓	✗
[16]	2024	C	4 m	6	country	✓	✓	✗
[22]	2024	C	5 m	6	city×5	✓	✓	✗
[23]	2024	C	9 m	5+	city×2	✓	✓	✓
[24]	2025	C	1 d	5+	city×2	✓	✓	✗
[25]	2025	C	1 w	2	site×3	✗	✓	✓
[26]	2025	C	1 y	10+	city×8	✓	✓	✗
[27]	2022	S	1 y	23M	city×1	✓	✓	✓
[28]	2022	S	2 y	17M	country	✓	✓	✗
[29]	2025	S	4 y	-	city×9	✗	✓	✗
[30]	2023	N	2 y	–	country	✓	✓	✗
Ours	**2025**	**N**	**5.5 y**	**30M+**	**country**	✓	✓	✓

- The situation is even more dire when looking at 5G SA, which has rapidly reached wide coverage thanks to dual-mode 5G antennas, yet generates negligible traffic that causes the typical 5G SA antenna to serve less than 5% of the traffic of a co-located 4G antenna.

Overall, these insights offer an unprecedented insider view on the complex path to making a new RAT like 5G successful –marked by massive CAPEX investments and slow, modest adoption and returns, even six years into deployment.

II. RELATED WORK

The deployment and performance of 5G networks have been the focus of numerous measurement studies in the past five years. Table I summarizes the most relevant works, which we discuss next by separating client-side investigations that take a User Equipment (UE) viewpoint and network- or provider-side ones that leverage infrastructure-level data.

Client-side measurements. The majority of the literature adopts a client-side perspective, collecting data from mobile devices connected to the radio access infrastructure. A considerable portion of these studies concentrates on brief time periods spanning days or weeks [10]–[12], [19], [24], [25], a small number of devices [7], [8], [25], [26], or restricted geographical areas such as a single campus or urban area [11]–[13], [17]. This includes early works benchmarking 5G against 4G in specific US cities [7], [8], [10], as well as more recent studies analyzing network performance in European cities [11], [13], comparing mobile operators [12], or examining performance in small-scale deployments [17], [24],

[25]. While these studies are valuable for providing detailed performance snapshots, their limited scope poses challenges in observing long-term network evolution.

A smaller set of client-side measurement studies considers a broader scale, either by covering longer time spans of several months to years, or wider geographical areas such as multiple cities or countries. These studies offer insights into the evolution of user-perceived performance [14], the maturity of 5G across global cities [26], and performance consistency across continents [15], [16], [22]. Other works focus specifically on the technical differences and application-level impact of NSA and SA deployments [9], [21], [23] or performance under high-mobility and cross-country scenarios [18], [20]. However, due to their client-centric nature, all these studies revolve around the Quality of Service (QoS) perceived by the end user and offer indirect, circumstantial observations (*e.g.*, on localized RAT availability) about the overall network infrastructure.

Network- and provider-side measurements. Far fewer studies are carried out from vantage points within the infrastructure or beyond it, primarily because they are only available to MNOs or mobile service providers. Yet, such network- or provider-side standpoints enable much more pervasive measurements and analyses. Prior works in this space utilize data from bandwidth speed test providers [28], [29] and live streaming platforms [27] to draw insights on technology adoption and performance trends across millions of users. However, the focus of these studies is on identifying the causes behind the underwhelming access bandwidth of 5G networks [28]; on the user experience that 5G provides for one specific service [27]; and on the evolution of 5G NSA coverage, throughput and latency in urban areas [29].

To the best of our knowledge, a single previous work adopts instead a MNO perspective, characterizing a nation-wide 5G deployment in the UK [30]. However, the focus of that study is on device heterogeneity; in terms of infrastructure, only broad trends of the incidence of different RATs are reported, and 5G resource utilization is analyzed just until 2022 and for NSA.

Compared to all prior works above, and as highlighted in Table I, the analysis that we present in this paper is the first multi-year study of the evolution of a 5G NSA/SA nation-wide infrastructure from the unabridged perspective of a major MNO. By investigating the RAN development until mid 2025 and characterizing its overall usage, our study complements the prospect of client-side measurements and brings major updates to the very thin literature based on network views.

III. METHODOLOGY

Our work builds upon data collected by Orange, the leading mobile network operator in France. The MNO provides customers with 4G and 5G access, as well as with legacy 2G and 3G connectivity that however nowadays serves less than 1% of the total mobile demand in the country and is thus excluded from our analysis. Next, we present the measurement setup, which is also illustrated in Figure 1, and the resulting datasets that we leverage for our downstream analyses.
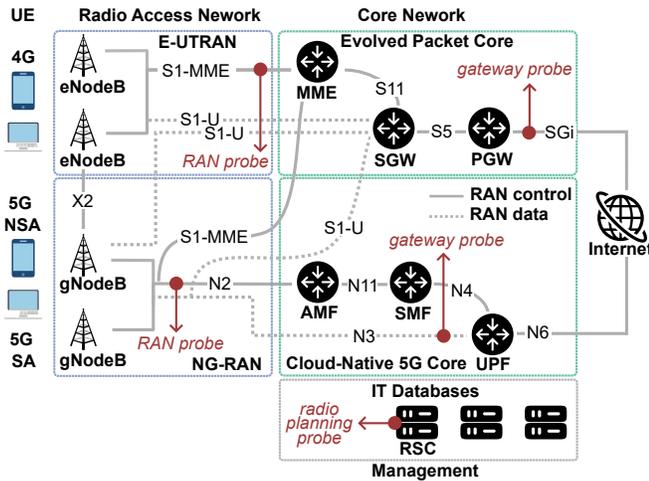
Fig. 1: Simplified 4G and 5G NSA/SA mobile network architecture. RSC stands for radio site configuration.

A. RAN deployment data

The MNO curates databases with detailed information on its RAN deployment. The *radio site configuration* database stores the location, development history, and current parametrization of each of over 350,000 antennas (*i.e.*, eNodeB and gNodeB) that compose the combined 4G and 5G radio access infrastructure of Orange in France. For each antenna, the database records spatial and technical information, including the site location, antenna orientation, environment (*e.g.*, indoor or outdoor), technology, frequency band, and operational status (*e.g.*, planned, under testing, active, or decommissioned). This database is stored in the centralized IT system within the MNO's internal management system and is continuously updated by multiple operational units responsible for the planning and physical upgrading of the RAN. We probe the database and extract weekly snapshots of the status of the whole 4G/5G radio access infrastructure, which allows tracking the RAN evolution from January 2020 to July 2025.

B. Mobile data traffic

The traffic measurements are continuously collected by the MNO from July 31, 2023 to July 31, 2025, using passive measurement probes tapping at both RAN and CN equipment.

As shown in Figure 1, the probes deployed at the S1-MME interface of the 4G Mobility Management Entity (MME) capture signaling data associated with both 4G eNodeBs and 5G NSA gNodeBs. Similarly, for 5G SA traffic, the N2 interface at the 5G Access and Mobility Management Function (AMF) is monitored for the mobility control operations. These RAN probes allows geo-referencing traffic sessions, by associating them to a specific serving antenna and its physical location.

The CN probes collect instead information about the served data traffic. IP sessions generated by 4G and 5G NSA users are monitored at the SGi interface of the 4G Packet Gateway (PGW) that connects to external Packet Data Networks (PDNs). Regarding the sessions generated by 5G SA users, they are monitored at the N3 interface, which connects the

gNodeB to the 5G User Plane Function (UPF), carrying the user data traffic within the 5G core. We remark that information collected at the MME, namely Packet Data Protocol (PDP) context session data and *secondary* traffic indicators, is used to correctly label 5G NSA traffic transiting through the 4G Evolved Packet Core (EPC).

The joint measurements from RAN and CN passive probes let the operator determine the volume of mobile traffic served by individual antennas in the 4G and 5G NSA/SA infrastructure. For the purpose of this study, the antenna-level traffic loads are aggregated in time with a 15-minute resolution.

C. Supplementary data

To carry out parts of our study we also employ data and statistics provided by the French National Institute of Statistics and Economic Studies (INSEE). In particular, we consider two different subdivisions of the French territory defined by INSEE based on geographical and demographic criteria: IRIS zoning and commune zoning. On the one hand, IRIS zones are the finer-grained statistical units used for analyzing population census data, and typically encompass a population of around 2,000 local inhabitants. On the other hand, communes are the smallest local administrative units in France and, depending on size and population, can be divided into multiple IRIS zones.

We then leverage census data across all communes in France to tell apart five urbanization levels: *rural*, *suburban*, *urban*, *metropolitan*, and *metropolitan centers*, which are characterized by population densities up to 40, 600, 2,500, 15,000, and beyond 15,000 inhabitants per km^2, respectively. Based on the defined urbanization levels, the French territory is distributed as 55.46% rural, 41.51% suburban, 2.39% urban, 0.61% metropolitan, and 0.03% metropolitan center. These figures are consistent with official reports indicating that the urban-rural typology in France comprises around half of predominantly rural regions, around 40% suburban regions, and less than 8% predominantly urban regions [31].

D. Ethical considerations

We analyze user-generated data consisting of transport-layer sessions in the Orange network. Spatiotemporal aggregations at carrier level and over 15-minute intervals render individual user sessions not identifiable, ensuring compliance with General Data Protection Regulation (GDPR) and protecting data subject privacy. The aggregation process is conducted within the secure infrastructure of the MNO by authorized personnel and under the guidance of the Data Protection Officer (DPO).

IV. UNDERSTANDING 5G DEPLOYMENT

We hinge upon the RAN deployment data presented above to provide a longitudinal overview of the evolution of the Orange 5G access infrastructure over more than five years and a half –since the launch of the technology until mid 2025.

A. Spatiotemporal evolution of the 5G RAN

We start by performing an exploration of the 5G infrastructure rollout along the temporal and spatial dimensions.
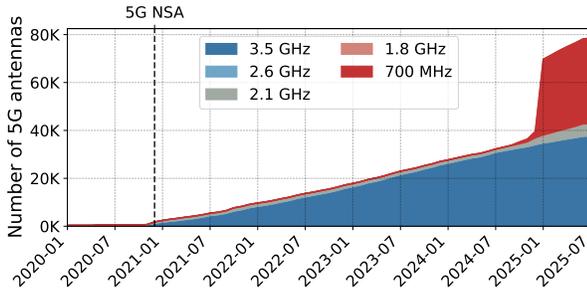
Fig. 2: Timeline of the deployed 5G antennas in the French territory since 2020. The data is separated by the commercial frequency bands operated by Orange in the country.
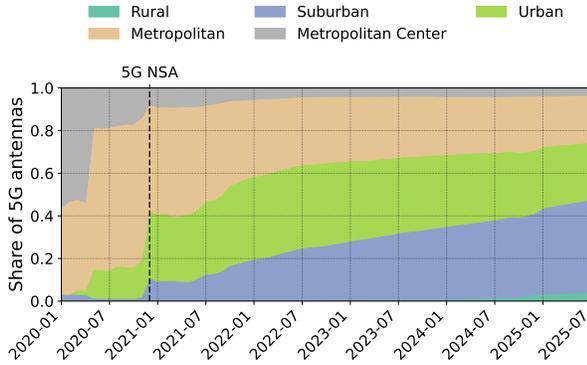

Fig. 3: Evolution of the 5G antenna distribution across urbanization levels, as percentages of the total deployed antennas.

Figure 2 provides a bird's eye view of the nation-wide 5G RAN deployment in time. The number of deployed antennas stayed low during 2020, which marked the initial phase of infrastructure deployment. Commercial 5G NSA services were open in December 2020, and the number of antennas has been growing steadily since. Notably, the growth has followed a neat linear trend through the years until the end of 2024. In this phase, the MNO has prioritized mid-band connectivity at 2.1 and 3.5 GHz –with a very strong prevalence of the latter, accounting for more than 97% of all antennas. These observations are well aligned with the common understanding of 3.5 GHz as the *core* distinguishing frequency for 5G.

A clear change appears instead with the start of 2025. The existing 5G RAN is very rapidly upgraded with a massive amount of low-band antennas. In just a few weeks, these antennas, operating at 700 MHz, have almost doubled the magnitude of the 5G transceiver elements in the country. Also mid-band antennas at 2.1 GHz have contributed to the sudden radio access augmentation, although in a much smaller way. Finally, it is worth noting that no millimeter-wave infrastructure is reported as licenses have not been yet issued for commercial services in the 26 GHz band in France [32].

Figure 3 gives an outlook on the spatial development of the 5G infrastructure, reporting the fraction of antennas present in each urbanization level defined in Section III-C over time. The prioritization in the coverage evolution is very clear. The initial phase of the RAN deployment –pre-commercial opening– almost exclusively focused on metropolitan areas,
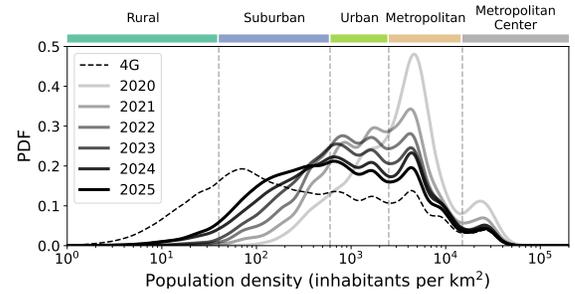

Fig. 4: Probability Density Functions (PDFs) of 5G antenna deployment across urbanization levels from 2020 to 2025. A reference PDF for the 4G deployment as of 2025 is included.
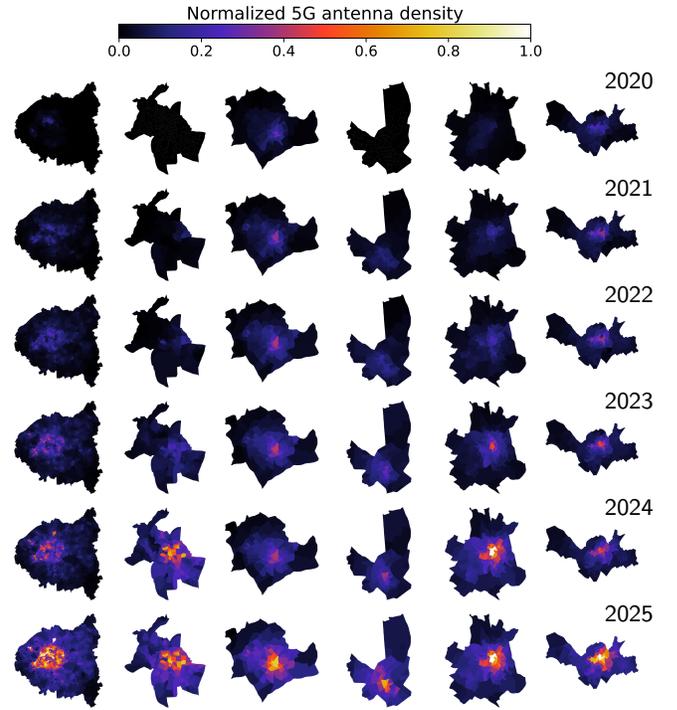

Fig. 5: Maps of the 5G coverage evolution in Paris, Lyon, Montpellier, Bordeaux, Toulouse, and Lille, respectively.

starting from their centers. However, from the moment when 5G connectivity started to be offered to the customers, the new RAT has been progressively covering more and more urban and suburban regions. As of mid 2025, around half of the 5G infrastructures covers cities, *i.e.*, metropolitan or urban areas, while the other half serves suburban regions. Rural lands are instead very marginally covered in the current stage.

Figure 4 depicts a more detailed spatiotemporal perspective. The plot shows the complete distribution of deployed 5G antennas across urbanization levels (on the abscissa) as measured on July 31 in each year. A clear evolution of the geographical spread of the radio access infrastructure emerges, from an initial bi-modal distribution centered in metropolitan areas in 2020, all the way to a much more uniform distribution that covers also urban and suburban regions in 2025. Interestingly, over the years the 5G distributions tend to that of 4G, which can be considered as an example of a mature RAT deployment.
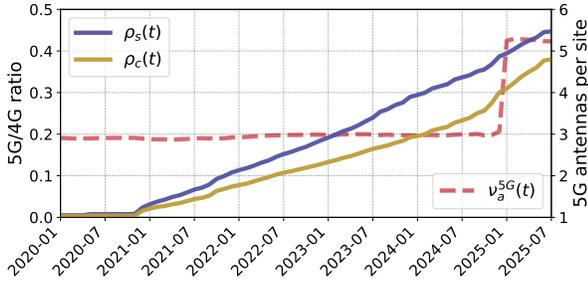
Fig. 6: Coverage $\rho_s(t)$ and $\rho_c(t)$, and capacity $\nu_a^{5G}(t)$ of the 5G RAN infrastructure between early rollout and mid 2025.

Visual illustrations of the 5G coverage evolution within individual cities of France are in Figure 5. We approximate the coverage of antennas via a Voronoi tessellation of space [33] and project the number of 5G antennas over individual IRIS zones $i \in \mathcal{I}$ as $\sum_{v \in \mathcal{V}} [T(v) \cdot A(i \cap v)/A(v)]$, where $v \in \mathcal{V}$ are Voronoi polygons of area $A(v)$ and $A(i \cap v)$ is the surface of the intersection between IRIS i and Voronoi polygon v. All maps highlight how the density of 5G antennas has grown substantially in the past two years in metropolitan areas –an effect previously hidden by the even greater investment that the MNO devoted to suburban regions in France.

Key insights: *Infrastructural efforts combine two strategies, i.e., a steady rollout of mid-band antennas and a sudden surge of low-band deployment in early 2025. 5G RATs have been incessantly augmenting in metropolitan areas since 2020, although the majority of the network is today dedicated to urban and suburban areas. Rural regions are not served yet.*

B. Coverage and capacity planning

Operators plan radio access infrastructures for *coverage*, to ensure that customers enjoy connectivity over the whole (*e.g.*, national) territory, and for *capacity*, to accommodate user demands that are strongly unbalanced over the geographical space and fluctuating in time. We now investigate the evolution of the Orange 5G RAN from those two perspectives. Let $a^{5G}(t)$, $s^{5G}(t)$, and $c^{5G}(t)$ be the number of active 5G antennas, operational 5G sites (*i.e.*, locations where a base station is placed, typically hosting multiple antennas and RATs), and French communes covered by 5G service, respectively; equivalent definitions hold for 4G. We then define:

- 5G/4G ratio of operational sites, $\rho_s(t) = s^{5G}(t)/s^{4G}(t)$;
- 5G/4G ratio of covered communes, $\rho_c(t) = c^{5G}(t)/c^{4G}(t)$;
- mean active 5G antennas per site, $\nu_a^{5G}(t) = a^{5G}(t)/s^{5G}(t)$.

Here, $\rho_s(t)$ and $\rho_c(t)$ measure the coverage attained by the 5G RAN, as they capture the geographical span of the 5G infrastructure with respect to 4G –in terms of sites and communes, respectively. Instead, $\nu_a^{5G}(t)$ gauges capacity, since it expresses the overlap of antennas at a same site, which does not improve coverage but increases the ability to serve traffic.

Figure 6 portrays the longitudinal evolution of the three metrics above. The coverage metrics $\rho_s(t)$ and $\rho_c(t)$ are characterized by a relatively constant growth since the launch of 5G services at the end of 2020. As of mid 2025, 5G

connectivity is present in almost half the 4G sites within the MNO network, and covers nearly 40% of the French communes. Knowing that 5G coverage prioritizes the most populated portions of the territory as seen in Section IV-A and considering recent INSEE demographics [34], the most recent value achieved by $\rho_c(t)$ lets us estimate that over 90% of the population has today access to 5G connectivity in France.

The dynamics of $\nu_a^{5G}(t)$ in Figure 6 are profoundly unalike. The number of active 5G antennas per operational site is constant at 3 until the end of 2024. The value reflects that 5G antennas are typically installed in triplets at a same site, ensuring $360°$ coverage with three sectors of $120°$ each. Entering 2025, a noteworthy, abrupt bounce in $\nu_a^{5G}(t)$ raises the value above 5. Jointly analyzing this result with Figure 2, it is apparent that the rise in 5G antennas per site is linked to the simultaneous and massive deployment of 700-MHz transceivers. We conclude that the low-band expansion of the RAN in early 2025 is primarily aimed at improving the 5G capacity, with the new antennas installed at existing 5G sites and providing coverage overlap to the 3.5-GHz antennas already present there. Indeed, the concurrent availability of mid- and low-band capacity paves the way for Carrier Aggregation (CA), *i.e.*, the possibility for 5G UE to boost throughput by exchanging data over the different available bands in parallel.

When we break down the results in Figure 6 across the urbanization levels defined in Section III-C, a clear diversity of deployment strategies for coverage and capacity comes into view, depending on the population density of the target area. Figure 7a shows that the evolution of coverage of the existing 4G sites has been constant in all urbanization levels, excluding rural regions that, as already observed, only recently started to receive 5G service. However, the coverage expansion rapidity has not been the same in metropolitan, urban, and suburban areas: site coverage has proceeded much faster in metropolitan and urban areas, where 80% of the 4G sites feature today 5G antennas; that figure is instead below 50% for suburban areas. Very densely populated metropolitan centers also show a reduced site penetration, but in that case the reason is the unusual concentration of 4G sites, which are still much more pervasive than 5G-enabled ones.

From a purely geographical viewpoint, Figure 7b shows a different story. Metropolitan centers have been covered for 90% of their surface just a few weeks into the launch of the commercial 5G offer by the MNO and enjoy today full coverage. Metropolitan and urban areas lags behind, in that order, but have reached near-100% coverage by mid 2025. Suburban regions are instead still scarcely covered.

Finally, in contrast with the coverage analysis above, the timeline of the RAN infrastructure aimed at providing additional capacity is very homogeneous across urbanization levels, as seen in Figure 7c. The exact same pattern of $\nu_a^{5G}(t)$ observed for the overall deployment in Figure 2 characterizes metropolitan, urban, and suburban areas. This indicates that the augmentation of the radio access with low-band capacity has occurred synchronously across the whole nation-wide network and without prioritizing specific regions.
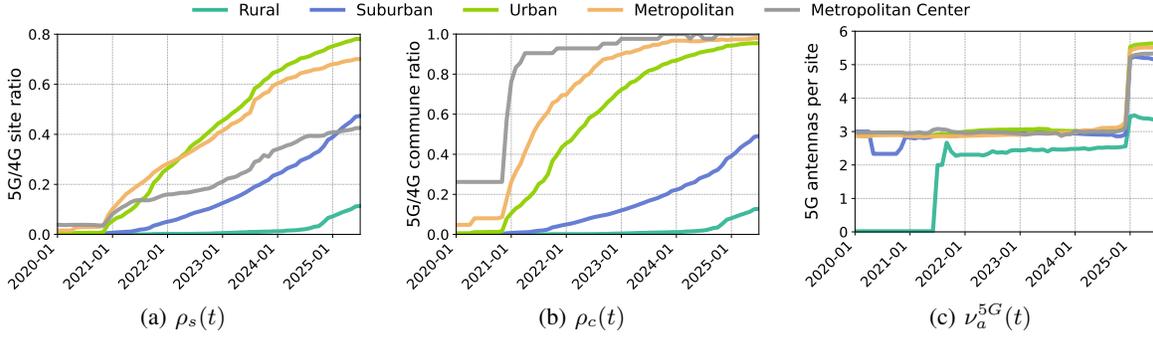
Fig. 7: Timelines of the deployment of coverage and capacity radio access infrastructure across urbanization level. (a) 5G/4G ratio of operational sites, $\rho_s(t)$. (b) 5G/4G ratio of covered communes, $\rho_c(t)$. (c) Mean active 5G antennas per site, $\nu_a^{5G}(t)$.
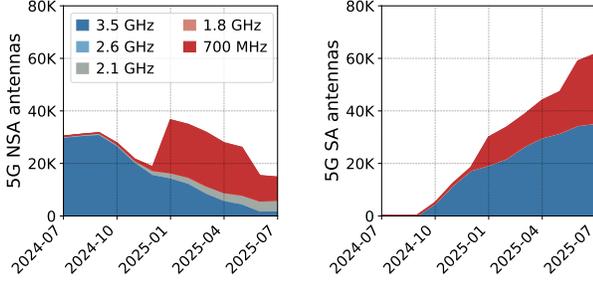

Fig. 8: Timeline of the operational 5G antennas in the French territory since July 2024, serving only NSA (left) or combined NSA/SA demands (right) and separated by frequency bands.

Key insights: *The 5G deployment under study has two phases. In the first half of the decade, it only aims at attaining coverage with mid-band spectrum by heavily prioritizing areas based on population density. In early 2025, a pervasive capacity boost is rapidly achieved using low-band antennas.*

C. 5G RAN from a SA viewpoint

5G SA is presently being rolled out by leading operators globally and Orange has launched commercial offerings of 5G SA services as early as October 2024. From a RAN infrastructure viewpoint, 5G antennas in the Orange network presently support a NSA/SA *dual mode*, *i.e.*, they can serve both NSA and SA UE as they are connected in parallel to the 4G and 5G cores [35] –a strategy that facilitates the transition between the two modes of operation [36]. Figure 8 breaks down the timeline in Figure 2 into antennas that exclusively serve NSA traffic (left) and those also serving SA demands (right). Both plots start at July 2024, when Orange initiated technical tests on its SA service.

The results show that, as soon as the commercial offer for 5G SA connectivity appeared, in October 2024, the 5G RAT begun to be increasingly used in dual-mode. The proliferation of this hybrid operation form has been constant and rapid in time and, as of mid 2025, over 80% of the 5G antennas serve UE in both NSA and SA modes. Still, a non-negligible number of sites does not serve 5G SA demands as per the left plot.

Figure 9 illustrates how the numbers above translate into coverage and capacity. 5G antennas operating in NSA/SA dual mode cover in mid 2025 around 40% of the 4G sites ($\rho_s(t)$)
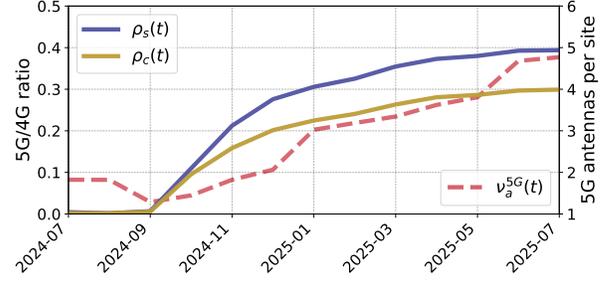

Fig. 9: Coverage $\rho_s(t)$ and $\rho_c(t)$, and capacity $\nu_a^{5G}(t)$ of the 5G SA infrastructure between early stages and mid 2025.

and 30% of the French territory ($\rho_c(t)$) after a quick growth in the previous 6 months. Such figures are not far from those relative to the full 5G deployment in Figure 6 and corroborate the rapid migration to dual-mode. The capacity ($\nu_a^{5G}(t)$) has improved along a similar pattern, and, by crossing results with those in Figure 6, all available antennas appear to be employed in dual-mode at sites where SA users are present.

Key insights: *The deployment of SA occurs much faster than that of NSA, as similar coverage and capacity levels are achieved in months instead of years. This is natural considering that, contrary to NSA, the activation of SA antennas is a software configuration and does not involve the time-consuming installation of new radio access hardware.*

V. CHARACTERIZING 5G UTILIZATION

Having examined the evolution of the 5G RAN infrastructure, we now study the adoption of the new technology by the mobile subscriber population. To this end, we leverage the network traffic measurements introduced in Section III-B, combined with the antenna deployment information. We remark that (*i*) our investigation is limited to user-plane traffic, focusing on the demands generated by the customers and not on control-plane signaling, and (*ii*) covers the period between mid 2023 and mid 2025, as 5G traffic was negligible before.

A. Overall 5G traffic and resource utilization

A high-level view of the temporal evolution of the overall 5G demand is provided Figure 10. The left plot juxtaposes the 5G traffic volume to its 4G counterpart, limited to sites where both technologies are present, hence providing a fair
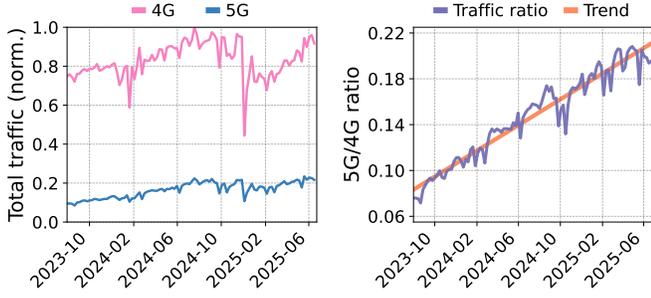
Fig. 10: Normalized total traffic in BS where 4G and 5G technologies coexist (left) and total 5G traffic volume normalized over 4G total traffic with weekly granularity (right).

comparison of the magnitude of the loads. The values are max-normalized since the served traffic is considered a sensitive metric by the MNO. Yet, the curves show the significant gap between the two RATs, with 4G accommodating a demand that is around 5 times larger than 5G. Interestingly, over the past two years, the difference does not seem to have been closing down, with the two curves growing at a similar pace.

The right plot in Figure 10 portrays instead the ratio of 5G-to-4G demands. This measure lets us better appreciate how the contribution of 5G to the total traffic volume is in fact constantly increasing, with a more than doubled ratio between the start and end of the two-year observation period. From a quantitative viewpoint, the incidence of 5G on the overall traffic has grown linearly from less than 10% to over 20%, with an increment of 0.5 percent points per month. We remark that the two plots in Figure 10 are consistent and show the two sides of the same phenomenon: 4G and 5G user demands have been increasing at a similar rhythm, preserving the absolute traffic gap, which inherently translates into a progressively higher prevalence of the RAT with the lower served volume.

However, observing total traffic volumes in isolation cannot offer a complete picture, in light of the diversity of deployments that characterizes 4G and 5G according to the results in Section IV. Let $v_s^{5G}(t)$ and $v_s^{4G}(t)$ be the total traffic volume recorded at site s at time t for 5G and 4G, respectively; in addition, let us define $a_s^{5G}(t)$ and $a_s^{4G}(t)$ as the number of 5G and 4G antennas at site s and time t. We then introduce:

- traffic per 5G antenna at s and t, $\tau_s^{5G}(t) = v_s^{5G}(t)/a_s^{5G}(t)$;
- traffic per 4G antenna at s and t, $\tau_s^{4G}(t) = v_s^{4G}(t)/a_s^{4G}(t)$;
- 5G/4G ratio of per-antenna traffic, $\rho_\tau(t) = \frac{1}{|\mathcal{S}|} \sum_{s \in \mathcal{S}} \frac{\tau_s^{5G}(t)}{\tau_s^{4G}(t)}$,

where $\mathcal{S}$ is the set of sites where both 4G and 5G RATs are deployed. Also, we recompute the mean active 5G antennas per site, $\nu_a^{5G}(t)$, only for sites in $\mathcal{S}$, obtaining a new metric $\nu_{a|\mathcal{S}}^{5G}(t)$; we calculate a similar value for 4G and define:

- 5G/4G ratio of per-site antennas, $\rho_a(t) = \frac{1}{|\mathcal{S}|} \sum_{s \in \mathcal{S}} \frac{\nu_{a|\mathcal{S}}^{5G}(t)}{\nu_{a|\mathcal{S}}^{4G}(t)}$.

The ratio $\rho_\tau(t)$ represents the traffic served by 5G antennas normalized by the demand handled by co-located 4G antennas, averaged over the whole RAN. The ratio $\rho_a(t)$ indicates instead how the density of 5G antennas compares to the 4G one at a same site, also averaged over all sites in $\mathcal{S}$.
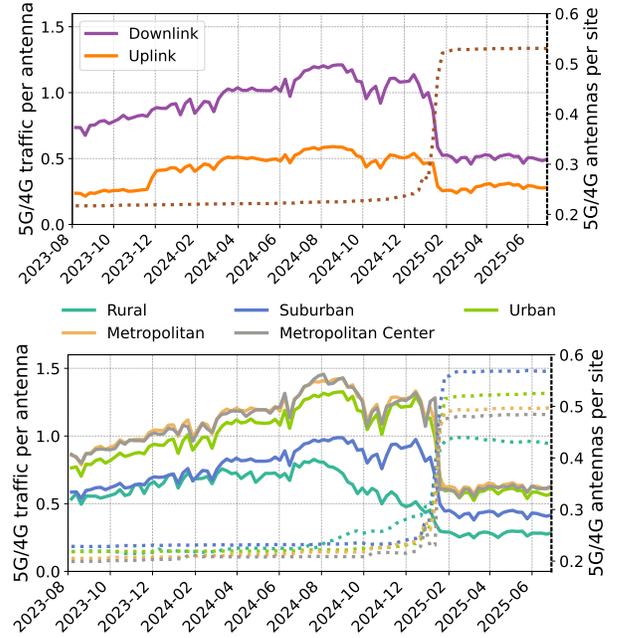

Fig. 11: Average per-antenna 5G/4G traffic ratio $\rho_\tau(t)$ separated by direction and mean per-site 5G/4G antenna ratio $\rho_a(t)$. Ratios are for sites with both RATs. Top: overall ratios in the whole RAN. Bottom: break-down per urbanization level.

The top plot in Figure 11 depicts the dynamics of $\rho_\tau(t)$ for traffic separated in the downlink and uplink directions. The demand served by the average 5G antenna has grown steadily between mid 2023 and late 2024 –from serving 20% less to 20% more downlink traffic than co-located 4G antennas. However, the massive deployment of low-band 5G capacity in 2025 has not been accompanied by a matching growth in the 5G load, thus causing $\rho_\tau(t)$ to plummet in the new year. Interestingly, 5G users appear to induce demands that are proprtionally much higher in downlink than in uplink, for which 5G antennas barely serve more than half the traffic of co-located 4G ones even during the peak activity at the end of 2024; this is in fact consistent with demands observed in prior studies about 5G service consumption [37].

The timeline of $\rho_\tau(t)$ is divided across urbanization levels in the bottom plot of Figure 11. The overall pattern stays the same commented above but scales differ. In metropolitan and urban areas, 5G antennas peak at serving 50% more than local 4G antennas in late 2024. In suburban and rural areas, the maximum $\rho_\tau(t)$ stays below one. Clearly, more densely populated regions exhibit a much faster adoption of the new technology, although all urbanized regions show close patterns and, *e.g.*, users in ultra-dense metropolitan centers are not earlier adopters than customers in middle-sized cities.

Finally, the evolution of $\rho_a(t)$ is unsurprising in the top plot of Figure 11, where it closely mimics that of $\nu_a^{5G}(t)$ in Figure 6. Instead, the bottom plot unveils differences among urbanization levels after the installation of low-band capacity: in particular, metropolitan and urban areas yield lower per-site antenna ratios, implying that not only the 4G RAN deployment

TABLE II: 5G SA capable mobile devices through 2025.

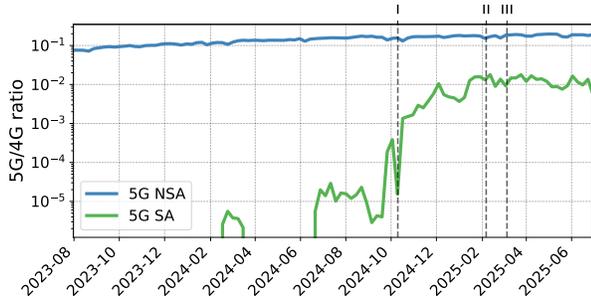| Date	Brand	Added models	Total
March	Samsung (6)	S25, S25 Plus, S25 Ultra, S24, S24 Plus, S24 Ultra	11
	Xiaomi (4)	14, 14T, 14T Pro, 13T Pro	
	Honor (1)	Magic7 Pro	
May	Samsung (1)	A26	16
	Xiaomi (3)	Redmi Note 13, Redmi Note 13 Pro, 13T	
	Honor (1)	Magic7 Lite	
July	Samsung (12)	S23, S23 FE, S24 FE, S25 Edge, A16, A35, A36, A56, A53 FE, Z Fold7, Z Flip7, Z Flip7 FE	36
	Honor (1)	Magic V3	
	Apple (7)	15, 15 Plus, 16, 16e, 16 Plus, 16 Pro, 16 Pro Max	

Fig. 12: Timeline of the nation-wide demand for 5G NSA and 5G SA normalized by the equivalent 4G traffic. Vertical lines indicate milestones in the rollout of 5G SA for (I) home connectivity, (II) enterprise customers, and (III) general public.

features more sites in metropolitan centers (as commented in Section IV-B) but also the density of 5G antennas per site is slower in catching up with 4G within cities.

Key insights: *5G adoption is steady but slow as the incidence of the technology on the nation-wide mobile data traffic grows just 0.5% a month. The 5G infrastructure is largely underutilized as of mid 2025, with the typical 5G antenna serving half the demand of co-located 4G antennas despite a 5× higher capacity seen in trials [38] and production [30].*

B. A focus on SA traffic and adoption

The recent commercialization of 5G SA by the MNO represents a unique opportunity to investigate the early adoption of the new service by the local mobile subscribers. Orange introduced 5G SA, under the commercial designation 5G+, in three phases to date, as marked in Figure 12: (i) a fixed-wireless service intended for *home* environments in October 2024; (ii) a mobile rollout dedicated to *enterprise* customers in February 2025; and (iii) a full mobile service open to the *general public* in March 2025.

Several important considerations concerning the SA service are also in order. First, not every UE natively support SA and, in fact, official data from Orange indicates that the UE ecosystem may be dominated by devices supporting NSA but lacking SA compatibility: namely, Table II reports the UE models that have progressively been confirmed to be SA-compatible by the MNO, showing that only 36 smartphone models can benefit
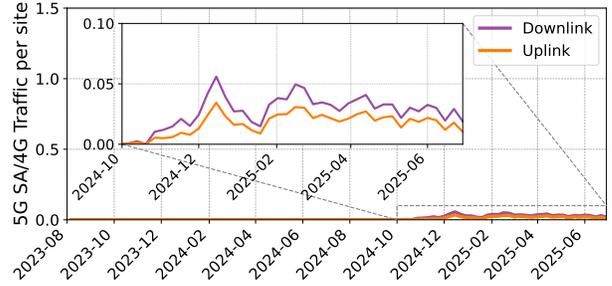

Fig. 13: Average per-antenna 5G/4G traffic ratio $\rho_\tau(t)$ when the 5G traffic is restricted to demands generated by SA users.

from SA services as of mid 2025. Second, even in presence of a compatible UE, 5G contracts are not automatically upgraded to SA but require opt-in by the subscribers; although this has no associated cost, it may still create a barrier to adoption. Third, specific incentives to attract users to embrace the SA service seem lacking, as the commercial 5G+ specifications indicate a maximum downlink throughput of 1.5 Gbps (with two-band CA) with SA, versus a 2.1 Gbps peak capacity (with four-band CA) for the standard 5G, *i.e.*, NSA [39].

The very recent introduction of 5G SA, in combination with the different considerations above, translate into a meager traffic demand generated by SA users, shown in Figure 12. The first significant SA loads appear with introduction of the home service in fall 2024 and stabilize at around one order of magnitude below 5G NSA; since the traffic volumes are normalized by the 4G one in the plot, SA users induce a traffic that is in fact just 1% of that of 4G customers. Remarkably, the introduction of mobile services in early 2025 does not produce any significant change in the SA load, while NSA keeps growing in the same period and is thus the sole responsible for the overall 5G traffic increase observed in Section V-A.

The limited user demand translates into little utilization of the available radio resources, in Figure 13. The plot reports the 5G/4G traffic ratio for co-located antennas, $\rho_\tau(t)$, when only 5G SA traffic is considered. Here, the average 5G antenna serves a SA demand that is just 2–4% of that created by mobile subscribers at co-located 4G antennas. Also for this metric, it is hard to appreciate any positive trend in the adoption of the SA service over time.

Finally, Figure 14 provides another angle on user adoption of the different RATs. The figure shows the Empirical Cumulative Distribution Function (ECDF) (top plot) and PDF (bottom three plots) of the percentage of *serving* time, *i.e.*, the fraction of time intervals during which a given antenna observes a non-zero traffic demand hence is not idle. To compute the distributions, we consider all 15-minute time slots in the period between October 2024 and July 2025, *i.e.*, the period during which the SA offering is available to Orange customers in France, and count the proportion of such slots during which each 5G (respectively, 4G) antenna exchanges traffic with 5G NSA or SA (respectively, 4G) mobile devices. Note that we consider the actual life time of each antenna to compute its percentage of serving time, so as not to penalize antennas that are operational only during a fraction time since October 2024.
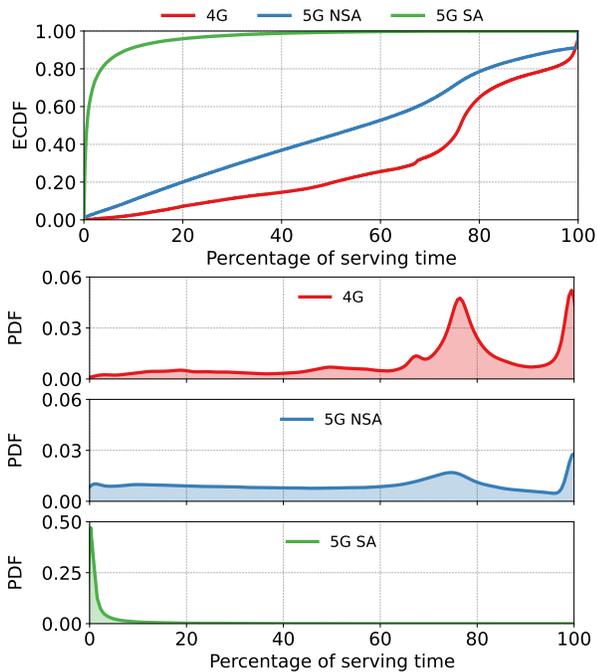
Fig. 14: ECDF (top plot) and PDF (bottom three plots) of the percentage of non-idle 15-minute time slots recorded at 4G and 5G antennas. Distributions for 5G are separated by the traffic generated from NSA and SA devices.

The utilization of a mature RAT infrastructure such as 4G is characterized by around 20% of antennas with reduced of serving time below 60%: most likely, these antennas provide coverage to rural areas with a sparse user population that is not active all the time. Then, a bi-modal distribution tells apart a first group of antennas active around 80% of the time, *e.g.*, due to overnight lack of traffic or power-off policing [40], and a second set with near-100% activity over time.

The utilization of 5G antennas due to NSA traffic tends to approximate the behavior observed for the 4G RAN. Indeed, the same pattern emerge, although the faction of underutilized antennas is much higher, at around 60%, due to the lower number of 5G NSA customers compared to 4G. The shape of the ECDF and PDFs is instead very different when looking at 5G antenna utilization from SA users. Here, almost 100% of the available 5G antennas are simply never used by SA mobile devices –further highlighting the lack of adoption of the technology during the observed time frame.

Key insights: *The expeditious deployment of 5G SA, thanks to the activation of an NSA/SA dual mode at 5G antennas, has not yet been matched by a significant adoption by the user base. Instead, the traffic generated by SA-compatible devices is using a tiny fraction of the available antenna capacity and induces negligible load on the radio access infrastructure.*

VI. Discussion and conclusions

Our longitudinal investigation of the level of RAN development and user adoption of the 5G technology in France, performed from the privileged vantage point of a leading global MNO, reveals the stark contrast between the infras-tructural investments of the operator and the user adoption of the new technology. In the five years that have elapsed since the launch of 5G services in the country, the coverage of the new RAT has been steadily growing, from metropolitan areas outwards, and in mid-2025 provides coverage to 90% of the French population. In parallel with a continued expansion of (now adequate) coverage, the MNO is also starting to deploy capacity antennas at 5G sites so that its customers can benefit from higher service availability and improved bandwidth via CA techniques. On top of these antenna deployment upgrades, the operator has recently activated a NSA/SA dual-mode at the 5G antennas, which has granted pervasive access to SA services within just a few weeks. Clearly, all these evolutions of the 5G RAN imply a sustained and very sizeable Capital Expenditure (CAPEX) for the operator.

However, the return on investment seems far to come for the MNO as our measurement study also reveals a severe under-utilization of the deployed 5G capacity: as a representative figure, the typical 5G antenna serves half the traffic of a co-located 4G antenna, despite an acclaimed $5\times$ higher capacity. Indeed, the adoption of the technology by the subscriber base is rather quiet and, 5 years after launch, 5G is responsible for just 16% of the total mobile data demand served by the multi-RAT network of the MNO. At the current growth rate of 0.5% per month in overall mobile traffic incidence, a simplistic projection indicates that 5G demand would take over 10 more years to match the 4G one. In addition, over 95% of such 5G load is from the NSA service, as the recent commercialization of SA seems to have gone somewhat unnoticed by customers.

While our observations are specific to one particular country and MNO and their generalization remains to be confirmed, we believe that the findings above offer novel insights on the real-world challenges that the maturing 5G technology may face. For instance, our results quantify the inherent temporal disconnect between the CAPEX associated to a new RAT and the revenues from user adoption, which seems to be especially harsh in the studied case. This spurs conversations on the necessity of targeted policies by local governments to support the MNO effort in providing state-of-the-art mobile services to the citizens. It also raises questions on the marketing strategies that operators adopt, which in the presented case do not seem effective –especially in the case of 5G SA with opt-in requirements and unclear incentives for the end user.

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