

Coverage and Performance Analysis of 5G Non-Standalone Deployments

Konstantinos Kousias
Simula Research Laboratory, Norway

Mohammad Rajiullah
Karlstad University, Sweden

Giuseppe Caso
Ericsson Research, Sweden

Ozgu Alay
University of Oslo, Norway

Anna Brunstorm
Karlstad University, Sweden

Luca De Nardis
Sapienza University of Rome, Italy

Marco Neri
Rohde & Schwarz, Italy

Usman Ali
Sapienza University of Rome, Italy

Maria-Gabriella Di Benedetto
Sapienza University of Rome, Italy

ABSTRACT

Fifth Generation (5G) networks are becoming the norm in the global telecommunications industry. In this paper, we present the first large-scale measurement study on commercial 5G Non Standalone (NSA) deployments in a European country. We leverage the collected dataset, which covers two Mobile Network Operators (MNOs) in Rome, Italy, to first, study network deployment and radio coverage aspects, and second, explore the performance of two use cases related to enhanced Mobile Broadband (eMBB) and Ultra-Reliable Low Latency Communication (URLLC). Results show that 5G NSA can provide higher downlink throughput and slightly lower latency compared to Fourth Generation (4G) systems. However, performance is influenced by several factors, including propagation conditions, system configurations, and handover events, ultimately highlighting the need for further system optimization.

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1 INTRODUCTION AND BACKGROUND

Fifth Generation (5G) cellular systems are developed to address high bandwidth, low latency, and massive connectivity requirements of enhanced Mobile Broadband (eMBB), Ultra-Reliable Low Latency Communication (URLLC), and massive Machine-Type Communication (mMTC) use cases. Therefore, compared to Fourth Generation (4G) technologies, i.e., Long-Term Evolution (LTE) and LTE

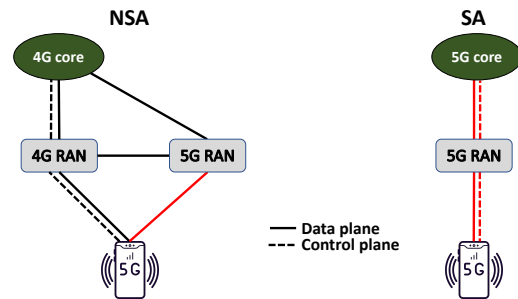


Figure 1: A schematic diagram of 5G NSA and 5G SA.

Advanced (LTE-A)¹, 5G systems are expected to satisfy more demanding and heterogeneous Quality of Service (QoS) and Quality of Experience (QoE) requirements, e.g., in terms of throughput, latency, and reliability.

To support such requirements, the 3rd Generation Partnership Project (3GPP) has standardized two main 5G deployment modes in Release 15 (Rel-15), i.e., Non-Standalone (NSA) and Standalone (SA) [10]. The main difference is that 5G NSA relies on the existing 4G core network for control plane management, while 5G SA uses its own 5G core, hence, acting independently of the 4G network (Figure 1). Both modes require a 5G New Radio (NR) Radio Access Network (RAN) composed of Next Generation Node Bs (gNBs), i.e., the 5G equivalent of 4G E-UTRAN Node Bs (eNBs), and corresponding Physical Cell IDs (PCIs), i.e., a reusable cell identifier at the physical layer, which can operate in low (< 1 GHz), mid (1-6 GHz), or high (> 24 GHz) frequency bands.

In the ongoing 5G deployment stages, the majority of Mobile Network Operators (MNOs) decided to adopt the NSA mode, since it is a more straightforward and less costly solution. However, 4G/5G co-dependence in NSA introduces several challenges in terms of configurations, procedures, and performance, that require further study and investigation. Therefore, it is key to understand the implications of the NSA architecture on coverage, performance, and network management (e.g., gNB placement strategies, handovers, resource allocation, network configurations, and so on).

In the above context, two main technologies are used for improving network performance, namely Synchronization Signal Block

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¹For the sake of brevity, 4G LTE and LTE-A will be referred to as 4G for the rest of this paper.

(SSB) beamforming and Dual Connectivity (DC). On the one hand, SSB beamforming is a technique that uses multiple propagation beams (up to 8 in mid-band, as per Rel-15) to direct the 5G signal toward different User Equipments (UEs); SSB beam (re-)selection depends on the encountered network coverage conditions, and is critical for increasing spectral efficiency and coverage, particularly at high frequency, e.g., millimeter wave (mmWave) [5]. On the other hand, DC allows a UE to be simultaneously connected to and exchange data with 4G and 5G PCIs, aiming to increase data rate and reliability [2, 4].

Over the last few years, research has been conducted aiming to empirically characterize the performance of 5G. Xu et al. [15] analyzed commercial 5G mid-band networks in China, focusing on coverage, throughput, latency, and device energy consumption aspects. Likewise, Narayanan et. al. [11] conducted a measurement study on 5G mid-band and mmWave networks in the US, thus establishing a performance baseline for early commercial 5G deployments. They later introduced a Machine Learning (ML) framework for 5G throughput prediction in [12], and analyzed power consumption and QoS/QoE aspects in [13] and emerging challenges for video streaming applications in [14].

In this paper, we present a large-scale measurement study on the commercial 5G mid-band NSA networks of two major MNOs in Rome, Italy. To the best of our knowledge, this work constitutes the first effort toward empirically studying deployment, coverage, and performance aspects of 5G NSA deployments in a European country, as well as providing insights with regard to SSB beamforming and DC technologies. In addition, in terms of QoS/QoE performance, we study throughput and latency/reliability aspects, by using the Speedtest by Ookla² and a dedicated test for real-time online gaming by Rohde & Schwarz (R&S)³, to showcase achievable performance for eMBB/URLLC-like services. We compare our findings on 5G NSA against 4G measurements. Our contributions are as follows:

- We carry out a large-scale measurement campaign on 4G and 5G NSA cellular networks in Rome, Italy, during a period of approximately 7 weeks (Section II). In addition, we open-source the collected dataset to allow for further analysis and investigation.⁴
- We present a comparative analysis of radio coverage and network deployment strategies between two MNOs in Italy (Section III).
- We explore the performance of 4G and 5G NSA by focusing on throughput and latency/reliability aspects, executing an extensive analysis across different scenarios (Section IV).

The paper is organized as follows. Section 2 describes the experimental design and provides details on the collected dataset. Section 3 demonstrates results on network deployment and radio coverage, while Section 4 analyzes QoS/QoE performance. Last, Section 5 concludes the paper.

2 EXPERIMENTAL DESIGN AND DATASET

This section presents the measurement campaign and provides a description of the collected dataset.

2.1 Measurement Setup and Configuration

We performed a large-scale measurement campaign for two major Italian MNOs, denoted as Op_i ($i \in [1, 2]$) in the following, offering both 4G and 5G coverage in Rome, Italy, during a period of 7 weeks between December 2020 and January 2021.

Measurement Scenarios: The campaign was organized in *sub-campaigns* carried out during different day types (weekdays vs. weekends) and times of the day. The sub-campaigns were conducted in heterogeneous geographical areas and under different mobility scenarios, that is: *Indoor Static (IS)*, for measurements performed at the 7th floor of a residential building, and different locations (offices and laboratories) at the 2nd floor of the Department of Information Engineering, Electronics and Telecommunications (DIET) of Sapienza University of Rome; *Outdoor Walking (OW)*, for measurements performed outdoor while walking with an average speed of 3.63 km/h; and *Outdoor Driving (OD)*, for measurements performed outdoor while driving a private vehicle (car) with an average speed of 17.36 km/h. In both mobile scenarios, the average speed is significantly affected by the encountered traffic and road conditions (e.g., traffic lights, road congestion, etc.).

Measurement System: The campaign was carried out using the R&S TSMA6 toolkit, an integrated system composed by an embedded Intel PC running Windows and a network/spectrum scanner. The PC was used to run the R&S ROMES software, which allowed for real-time visual inspection, campaign replay, and data storing/exporting. As shown in Figure 2, the TSMA6 toolkit was equipped with i) a synchronized GPS antenna to enable the geo-mapping of the locations where measurements were collected, ii) a commercial 5G-capable device (Samsung S20) for performing active measurements, and iii) a Radio Frequency (RF) omnidirectional antenna to allow for the continuous passive scanning of downlink control signals from operational 3GPP technologies. The scanner was configured to perform passive measurements on four 4G bands, i.e., Bands 1 (2110-2170 MHz), 3 (1805-1880 MHz), 7 (2620-2690 MHz), and 20 (791-821 MHz), and one 5G band, i.e., Band n78 (3.3-3.8 GHz). We used the R&S Android application called *Qualipoc* for running the active measurements, i.e., QoS/QoE tests.

2.2 Measurement Methodology

To evaluate the performance of the networks under analysis, we used both passive and active measurements.

Passive Measurements: We used the scanner to detect and decode downlink control information, aiming to infer network deployment and coverage characteristics. Due to the high scanner sensitivity, the collected data is representative of the coverage experienced by the UE in the same area, but also includes information on signals that a normal UE may be not able to detect and decode (e.g., signals from distant PCIs), thus allowing for a finer analysis.

To represent each measurement, we use the notation $m_{lat, long}^{freq}$, where $[lat, long]$ and $freq$ are the estimated geo-location coordinates pair and the operating carrier frequency, respectively. For 4G, $k \geq 1$ measurement samples were recorded at each location, where

²www.speedtest.net. Accessed on July 10, 2022.

³www.rohde-schwarz.com/us/products/test-and-measurement/network-data-collection/qualipoc-android_63493-55430.html. Accessed on July 10, 2022.

⁴https://zenodo.org/record/7026073#.YwkNi-xBy3I

	Passive (samples)				Active (sessions)											
RAT	4G		5G		4G				5G Partial				5G			
App	-				Speedtest		Gaming		Speedtest		Gaming		Speedtest		Gaming	
MNO	Op ₁	Op ₂	Op ₁	Op ₂	Op ₁	Op ₂	Op ₁	Op ₂	Op ₁	Op ₂	Op ₁	Op ₂	Op ₁	Op ₂	Op ₁	Op ₂
IS	89.6K	127K	553K	3.8M	75	49	68	107	50	21	6	9	4	45	79	48
OW	112K	114.8K	456K	2.51M	38	147	264	176	4	18	13	14	1	6	37	33
OD	41.1K	42.9K	156.5K	1.02M	10	31	93	39	10	27	21	7	1	14	76	32

Table 1: Dataset statistics per scenario and grouped by MNO, application (active dataset), and RAT/session type. We report the number of samples and sessions for the passive and active datasets, respectively. Note that the passive dataset contains additional measurements (beyond the active counterpart measurements) that we use for a more rigorous statistical analysis.

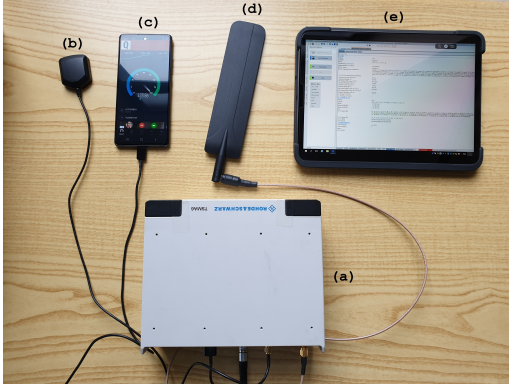


Figure 2: The measurement system consisting of (a) the R&S TSMA6 toolkit, (b) a GPS antenna, (c) a commercial 5G-enabled device, (d) an RF antenna, and (e) a tablet for monitoring the laptop (i.e., embedded in the TSMA6 box) where the ROMES software was running.

k represents the number of detected 4G PCIs in that location. For 5G, due to the possible use of SSB beamforming, measurements were reported at SSB beam level. Hence, for each 5G PCI, the scanner decoded the characteristics from $1 \leq l \leq 8$ SSB beams.

Active Measurements: We further performed active measurements through a 5G-capable UE (Figure 2), configuring it to perform QoS/QoE throughput and delay/reliability performance tests. Such measurement tests were repeated multiple times during each sub-campaign. We use the term *session* to refer to each repetition.

We adopted two UE modes: i) *5G-enabled*: the UE exposes its 5G NSA capability so that the network can decide to connect it to 5G PCIs along with 4G PCIs, and ii) *5G-disabled*: the UE only exposes its 4G capability so that the network only connects it to 4G PCIs. Therefore, sessions were partitioned as i) *5G*, when a 5G connection was available throughout the session, ii) *5G Partial*, when 5G was partially available during the session (with automatic fallback on 4G), and iii) *4G*, when only 4G was available. These latter sessions either belong to 5G-disabled campaigns or to 5G-enabled campaigns where a 5G PCI was never added as a further data carrier for the UE (e.g., due to 5G coverage holes). Next, we provide a brief description for each test.

2.2.1 Throughput Test. We used the Speedtest tool by Ookla to measure the end-to-end throughput in both 5G-enabled and 5G-disabled modes, with a target server located in Rome. The length of each session is of about 60 seconds. Speedtest uses TCP for performing throughput measurements, in single or multiple connections modes. We used the second option where, however, a closed algorithm is used for determining the number of connections.⁵

2.2.2 Latency/Reliability Test. We performed the real-time online gaming test provided by R&S Qualipoc to measure latency and reliability. Figure 3 shows the traffic pattern used for this test. The length of the active session for the real-time online gaming test is 10 seconds. The pattern aims to emulate different game interactivity phases, with a data rate between 0.1 and 1 Mbps. The exchanged UDP packets are subject to a delay budget, i.e., the client discards packets not received in time. 3GPP defines a 100 ms budget for this application class [1].

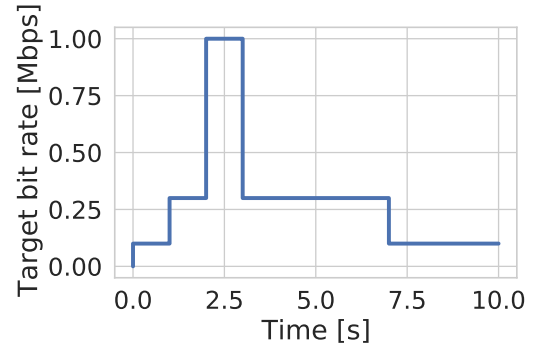


Figure 3: Traffic pattern used for emulating real-time online gaming services.

Qualipoc produces several Key Performance Indicators (KPIs), i.e., median Round Trip Time (RTT) (i.e., two-way latency), Packet Delay Variation (PDV), missed packet percentage, and a global interactivity score (*i-score*).

The median RTT is measured from the packets successfully returned to the UE, while the PDV is measured according to RFC 5481 [8]. Moreover, in addition to any lost packets, the missed packets include the packets exceeding the target delay budget of 100 ms. The missed packet rate is calculated as the ratio between missed

⁵help.speedtest.net/hc/en-us/articles/360038679354-How-does-Speedtest-measure-my-network-speeds-. Accessed on July 10, 2022.

packets and total number of sent packets. Finally, the *i-score* [%] is a QoE metric based on the above KPIs.⁶

2.3 Dataset statistics

Table 1 shows statistical information of the collected dataset for each scenario, grouped by MNO, application (for active measurements), and Radio Access Technology (RAT) vs. session type for passive vs. active measurements.

Passive dataset: We used a subset of the available features, including spatial and temporal fields, carrier frequency identifiers, and signal strength/quality indicators. For 4G, such indicators were measured on the Reference Signal (RS) sent by 4G PCIs; for 5G, they were measured on the Secondary Synchronization Signal (SSS), sent by 5G PCIs in the SSBs [6, 7]. Hence, for 5G, the dataset includes Secondary Synchronization Reference Signal Received Power (SS-RSRP), Secondary Synchronization Reference Signal Received Quality (SS-RSRQ), and Secondary Synchronization Signal to Interference and Noise Ratio (SS-SINR) at SSB beam level.⁷

The 4G and 5G passive datasets consist of approximately 527K and 8.48M samples, respectively (see Table 1). The 5G dataset size differs significantly between the two MNOs since, during our measurements, Op_1 was using a single SSB, while Op_2 adopted SSB beamforming with up to 8 SSBs.

Active dataset: We conducted 555 Ookla Speedtest measurement sessions (i.e., 197 for Op_1 and 358 for Op_2) and 1158 real-time online gaming sessions (i.e., 657 for Op_1 and 501 for Op_2). Table 1 shows the number of sessions for different scenarios, MNOs, and session types.

3 NETWORK DEPLOYMENT AND RADIO COVERAGE

5G NSA network deployment presents several challenges due to 4G/5G co-dependence and adopted carrier frequencies, among others, which may lead to reduced radio coverage and possible connectivity issues. Therefore, it is important to understand the deployment choices of the MNOs and study radio coverage characteristics in different scenarios.

3.1 Network Deployment

In this sub-section, we present network deployment statistics for each MNO and provide insights on the adopted SSB beamforming strategies.

3.1.1 Deployment density. Across all sub-campaigns, the scanner reported a total number of 313/162 and 407/158 4G/5G PCIs for Op_1 and Op_2 , respectively. At the time of our campaign, MNOs were collectively using around 30% of the available PCIs for 5G, indicating an ongoing 5G deployment. Additional information provided by ROMES on eNBs and Cell IDs (CIDs), i.e., a unique cell identifier at the physical layer, showed 125/441 eNBs/CIDs for Op_1 and 117/709 for Op_2 , i.e., a denser CID deployment for Op_2 .

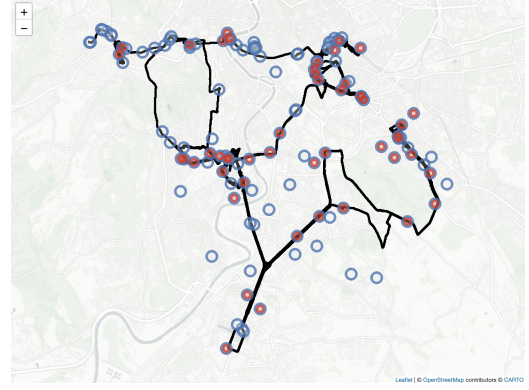


Figure 4: Spatial representation of the RAN deployment for Op_1 . The blue and red markers indicate the estimated positions of 4G eNBs and 5G gNBs, respectively. The black line in the background indicates the UE routes during the entire measurement campaign.

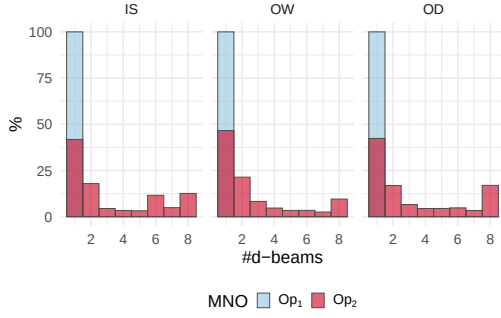
As a reference example, Figure 4 shows the eNB/gNB spatial distribution for Op_1 (similar results were obtained for Op_2 and omitted due to space constraints). We use different colors to differentiate between the two RATs, i.e., blue for 4G eNBs and red for 5G gNBs. The black line represents the UE OW and OD routes during the entire measurement campaign. Note that PCI position estimation is a feature provided by ROMES. To infer the position of each eNB/gNB, we perform additional processing (merging) of the data. In addition, for 5G, the position of the gNBs is approximated using the position estimates of the 5G PCIs and the nearest 4G eNB. We believe this is a reasonable assumption considering that in NSA the control plane is anchored to the existing 4G infrastructure; Therefore, gNBs are deployed on the basis of the 4G core and the 5G RAN overlaps with the 4G RAN. Overall, the results reveal that, at the time of the measurement campaign, the 5G RAN was still sparse compared to its 4G counterpart, possibly resulting in 5G coverage holes.

3.1.2 SSB beamforming strategies. Figure 5a depicts the density histogram of the *#d-beams* parameter, i.e., the number of detected SSBs per PCI at each location, grouped by scenarios and colored by MNO.

We observe that, at the time of the measurement campaign, Op_1 did not support SSB beamforming, hence, the percentage for *#d-beams*=1 across all scenarios is 100%. On the contrary, the scanner detected up to 8 SSB beams for the PCIs of Op_2 . In this case, we observe that the likelihood of detecting a single SSB beam is significantly higher than the rest *#d-beams* counts. This is due to the possible presence of locations with insufficient 5G coverage, where the high scanner sensitivity allows for detecting spurious SSBs from likely distant PCIs. Furthermore, for all scenarios, we see that the likelihood of detecting higher SSB beam counts becomes small with the exception of *#d-beams*=8. We believe this is due to the presence of locations with excellent 5G coverage (e.g., the scanner was in Line of Sight (LoS) with a given PCI), where although SSBs are beamformed, the scanner was still able to detect (e.g., due to signal reflection) and decode all the beams transmitted by surrounding

⁶www.rohde-schwarz.com/us/solutions/test-and-measurement/mobile-network-testing/stories-insights/article-interactivity-test-concept-and-kpis-part-2-253245.html. Accessed on July 10, 2022.

⁷The open-sourced dataset also provides additional features that cover a variety of 5G signals, i.e., Demodulation (DM), Physical Broadcast Channel (PBCH), Primary Synchronization Signal (PSS), and SS-PBCH.



(a) Density plot of #d-beams colored by MNO.

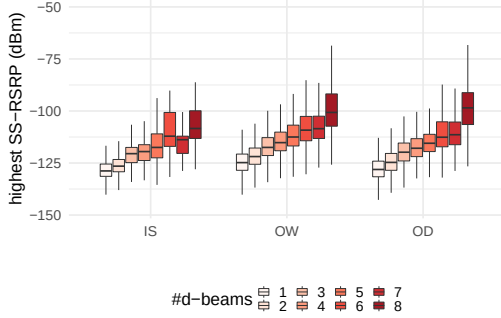
(b) Boxplot distribution of the highest SS-RSRP SSB beam across different #d-beams counts (Op_2).

Figure 5: SSB beamforming deployment analysis. Both sub-figures are grouped by scenario.

PCIs. Across scenarios, we did not notice significant differences. Therefore, as shown by our measurements, a 5G UE would not be able to detect and decode all the available SSBs from PCIs in urban scenarios unless it operates under good coverage conditions.

Figure 5b complements the above analysis by showcasing the significance of SSB beamforming in terms of network coverage by depicting the highest perceived SS-RSRP at each #d-beams count for Op_2 . For each scenario, the median values follow an increasing trend as #d-beams increases, i.e., the probability of achieving a higher SS-RSRP increases when multiple SSB beams are detected.

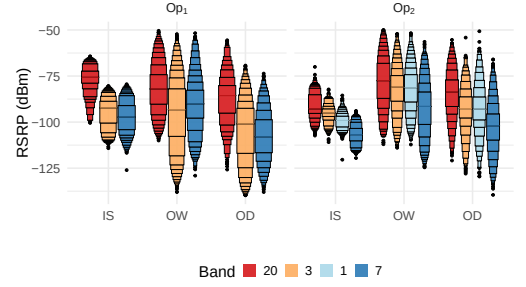
These results provide useful insights for better understanding 5G SSB beamforming and its impact on coverage, toward the derivation of strategies that MNOs can adopt for optimal 5G RAN planning and deployment.

3.2 Radio Coverage

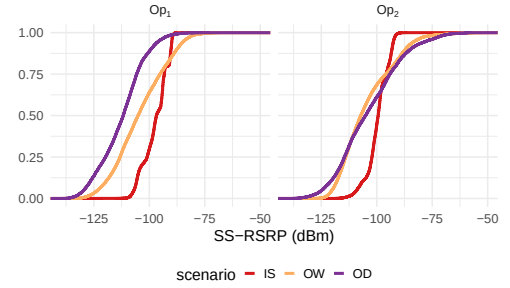
We now focus on the analysis of radio coverage, showing how it varies between MNOs and across different scenarios.

Given a location, radio coverage is determined as the highest Reference Signal Received Power (RSRP) (4G) and SS-RSRP (5G) perceived among all detected PCIs. To establish a performance baseline, we first look at 4G radio coverage.

Figure 6a depicts the distribution of the observed 4G RSRP in a letter-value plot format grouped by scenarios, dissected by MNOs, and colored by 4G carrier frequencies. We find that the two MNOs



(a) 4G.



(b) 5G.

Figure 6: Distribution of (a) 4G RSRP [dBm] across carrier frequencies (in a letter-value plot format and order by highest to lowest frequency) and (b) 5G SS-RSRP [dBm] (in an ecdf format), for Op_1 and Op_2 and grouped by scenario.

have quite different coverage properties. In particular, for Op_1 , the median RSRP for IS and OW scenarios is on par (-90.51 dBm and -89.05 dBm, respectively), while it decreases to -98.84 dBm for OD. On the contrary, Op_2 experiences the best and the worst RSRP conditions in OW (median value of -82.89 dBm) and IS (median value of -97.5 dBm), while the median RSRP is -92.92 dBm in OD. We also notice that, for both MNOs, the RSRP standard deviation increases between IS and OW/OD, with an average difference of 4 dB and 4.5 dB for Op_1 and Op_2 , respectively, which is expected considering that a mobile UE will experience higher coverage variability. Between the two mobility scenarios, the median RSRP shows a slow degradation as the UE moving speed increases, with an average RSRP difference between OW and OD of 9.79 dB and 10.03 dB for Op_1 and Op_2 , respectively. Last, across the available carrier frequencies, we observe a decreasing pattern for RSRP as the frequency increases, due to worse penetration and propagation properties of high frequency signals.

Figure 6b depicts the distribution of the 5G SS-RSRP as an empirical CDF function. For 5G, we observe that SS-RSRP is significantly higher in IS (median of -98.1 dBm across the two MNOs), while in OW/OD the UE experiences a decrease of 11.6 dB (Op_1) and 8.05 dB (Op_2). In addition, even though coverage conditions do not significantly vary across the two MNOs, there exists a 6.6 dB difference for SS-RSRP in OD in favor of Op_2 , which ties back to the use of SSB beamforming and further highlights its effect on coverage.

On par with the discussions in the previous sub-section, these results provide valuable insights on the performance of 5G mid-band radio coverage across different scenarios (e.g., indoor vs. outdoor, static vs. mobile). Such discussions can be further exploited toward efficient deployment and management of the 5G NSA infrastructure, and as a baseline for future 5G SA deployments.

4 APPLICATION PERFORMANCE

In this section, we present a comparative analysis of throughput and latency/reliability performance between 4G and 5G NSA networks.

4.1 Throughput Analysis

We start our discussion by presenting throughput results in both downlink and uplink directions.

4.1.1 Downlink Throughput. Figure 7 shows the achieved downlink throughput from Speedtest sessions in different scenarios, grouped by session type and MNO.

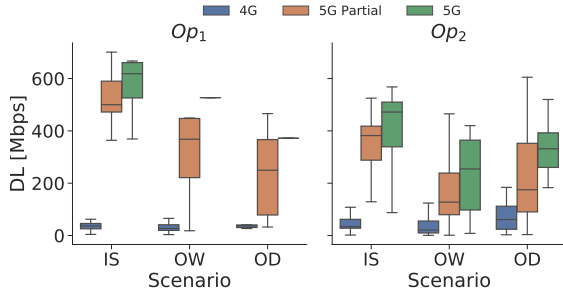


Figure 7: Downlink throughput grouped by MNO and scenario.

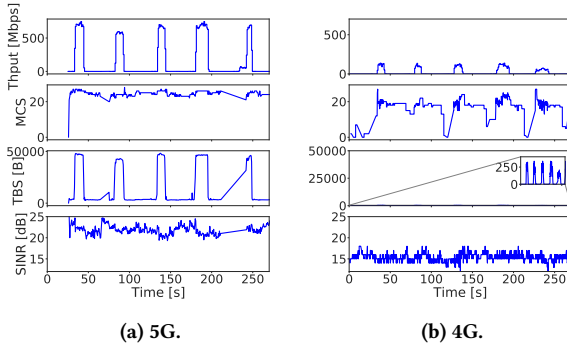


Figure 8: Example of downlink throughput for 5G (a) and 4G (b), with corresponding values of MCS, TBS, and SINR (Op_1 , IS scenario).

We observe that, in comparison to 4G, 5G (i.e., 5G and 5G *Partial*) provides significant downlink throughput gains. In IS, the 5G average median throughput values for Op_1 and Op_2 are 560 and 427 Mbps, respectively, with Op_1 providing the highest downlink throughput value of 701 Mbps in a particular 5G *Partial* session. In

contrast, the 4G median throughput values for Op_1 and Op_2 are only 34 and 39 Mbps, respectively.

The 5G throughput gain in IS reduces as the propagation conditions change in OW/OD, with the highest throughput variability experienced in 5G *Partial* sessions. These sessions include, by definition, cases when handovers from 4G to 5G, and vice versa, were executed. Therefore, these results suggest that the handovers executed in NSA due to unstable 5G coverage can be detrimental to throughput performance, as also observed in [11, 15].

In order to further analyze throughput performance, Figure 8 shows an example time series collected during a 5G-enabled (a) and a 5G-disabled (b) IS campaign for Op_1 . The first sub-figure of Figure 8a shows that the 5G downlink throughput achieves about 700 Mbps in most of the sessions. We also observe that 5G uses a Modulation and Coding Scheme (MCS) index up to 27 (second sub-figure) and consequently a modulation order up to 256-QAM, which is possible in radio conditions as good as the ones registered in these sessions (see the high SINR in the fourth sub-figure). Hence, as reported in the third sub-figure, 5G ends up using a high Transport Block Size (TBS) of around 50000 Bytes, as a result of the adoption of high MCS and possibly large allocated bandwidth, i.e., the resource blocks allocated to the UE. The total channel bandwidth is between 5-20 MHz for 4G systems, while it can reach up to 100 MHz for 5G mid-band networks [3]. In our measurements, we observed that both operators allocate a channel bandwidth of 78.120 MHz for 5G (resulting from subtracting 940 kHz of each guard band from a 80 MHz spectrum allocation, as per Italian regulation) as opposed to a maximum of 45 MHz for 4G as a result of varying level of carrier aggregation. When such a large TB is transported in a short Transmission Time Interval (TTI) of 0.5 ms (due to the sub-carrier spacing of 30 kHz adopted by both MNOs, as confirmed by our measurements), 5G achieves high throughput.

In the 5G-disabled scenario (Figure 8b), 4G shows lower throughput compared to 5G (around 100 Mbps, see first sub-figure), due to the allocated smaller channel bandwidth in 4G (mentioned above), the use of lower MCS index (< 20) (second sub-figure) and thus modulation orders. Hence, 4G uses a lower TBS (third sub-figure), which in turn explains the lower throughput. Good radio conditions were also observed for 4G (fourth sub-figure), but to a lower extent compared to 5G, a fact that has an impact on the choice of MCS and modulation.

As mentioned in Section 1, 5G NSA enables DC between 4G and 5G RATs [2]. In our dataset, we observe that Op_1 simultaneously uses 4G and 5G Physical Downlink Shared Channels (PDSCHs) when 5G is available along with 4G. Figure 9a shows a set of time series recorded during an IS campaign for Op_1 , where we see that the downlink throughput at the application layer (first sub-figure) consists of the aggregation of PDSCHs throughput from both 5G and 4G (second and third sub-figures). Figure 9b shows the results in the same location for Op_2 , where we see that Op_2 does not utilize DC, therefore, resulting in lower throughput.

4.1.2 Uplink Throughput. We now discuss the achieved uplink throughput in different scenarios and for different session types and MNOs.

Figure 10 shows the uplink throughput for each MNO. First, we observe that the 5G uplink throughput is significantly lower than

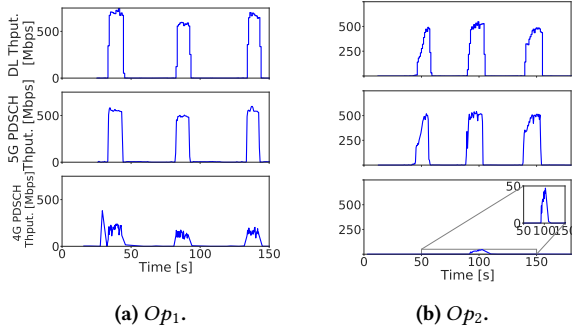


Figure 9: Example of different 5G and 4G PDSCH aggregation strategies for Op_1 (a) and Op_2 (b) in a IS scenario.

the downlink counterpart (Figure 7). This is justified by several factors, including UE power limitations and the use of the Time Division Duplex (TDD) scheme in the 5G mid-band under analysis. As indicated in our dataset, the adopted TDD pattern results in a downlink/uplink resource split of 7:2 slots, which significantly limits the uplink opportunities. We also observed lower MCS and modulation (up to 64-QAM), thus resulting in smaller TBS and lower achievable throughput (not reported due to space constraints).

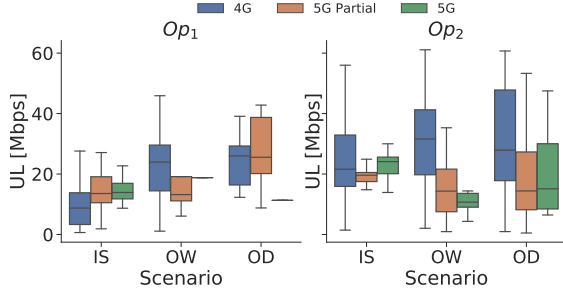


Figure 10: Uplink throughput grouped by MNO and scenario.

When comparing across scenarios, we see that, in IS, the 5G median uplink throughput is approximately 5 Mbps higher than 4G for Op_1 , while these two values are quite similar for Op_2 (a higher variability is registered for 4G). Surprisingly, for Op_1 , we observe that both 4G and 5G throughput in IS is lower than the throughput measured in the mobile outdoor scenarios (OW/OD). We explain this result by further inspecting both the usage of DC in UL and the 4G/5G coverage experienced by the UE during the corresponding measurement campaigns. First, we notice that, when DC is used, a large portion of the UL traffic is redirected on the 4G carrier, with only a small portion of it actually being transmitted on the 5G carrier. This is in contrast with the use of DC in DL (see Figure 9a for Op_1), where we observe that the 5G PCI carries most of the DL traffic. Second, we observe that the UE experiences worst average 4G coverage in IS compared to OW/OD, particularly in terms of RSRP (a similar 5G coverage is instead observed across the scenarios). These two aspects together lead to the conclusion that the 4G coverage has a significant impact on both 4G and 5G

UL throughput due to the pronounced use of the 4G carrier in both cases, with lower 4G coverage leading to lower throughput, as observed for Op_1 in IS. In this same scenario (Op_1 , IS), it is worth observing how, although not fully exploited, adding the 5G carrier in DC mode helps to slightly improve the performance, with 5G *Partial* and 5G sessions having higher throughput than 4G sessions.

In addition, in Figure 10, similarly to the downlink case, 5G performance seems more susceptible to mobility (OW/OD), likely due to coverage holes and variability. This results in throughput values lower than 4G, particularly for Op_2 . Overall, our results are in line with previous analyses [11] and suggest that MNOs have focused on assuring significant downlink throughput gains for the initial roll out of their 5G NSA networks, with the uplink counterpart requiring further enhancement.

4.2 Latency/Reliability Analysis

Beyond delivering high throughput, 5G is also expected to lower the communication latency toward supporting URLLC. In this section, we present the latency/reliability performance results obtained during the real-time online gaming tests.

Figure 11 shows the performance in different scenarios for 4G, 5G *Partial*, and 5G sessions.

Figures 11a and 11b show that 5G provides the lowest median RTT and PDV across all scenarios and MNOs. However, due to unstable 5G coverage, a high variability is observed for these KPIs in 5G *Partial* sessions, e.g., in OW/OD for Op_1 .

Figure 11c shows the missed packet percentage. Starting with Op_1 , there are almost no missed packets in either 4G or 5G sessions in all scenarios. However, there are missed packets in both mobile scenarios during 5G *Partial* sessions. This clearly shows that, similarly to the throughput case, 5G NSA handovers may lead to latency/reliability performance degradation. Figure 11d (top) shows the *i-score* for Op_1 . Having the lowest median RTT and PDV, and nearly no missed packets, 5G sessions provide the highest *i-score* in all scenarios. On the other hand, while 5G *Partial* sessions provide *i-score* similar to 4G in IS, they also provide the worst *i-score* in OW/OD due to increased missed packet percentage.

Moving to Op_2 , Figure 11c (bottom) shows almost no missed packet in IS for any sessions. However, both 5G *Partial* and 5G sessions suffer from missed packets in OW/OD. Hence, Figure 11d (bottom) shows that 5G sessions still provide the highest *i-score* in IS, but both 5G and 5G *Partial* have performance degradation in mobile scenarios.

As further detailed in [9], these results are tightly coupled with handover policies in 5G NSA. Indeed, if not carefully configured, such policies can lead to sub-optimal choices in adding/removing/using a 5G data carrier, eventually leading to performance losses that appear particularly detrimental for latency/reliability-sensitive services.

5 CONCLUSION

This paper presents the first empirical study on network coverage, deployment, and performance of 5G NSA deployments in a European country. We used the collected dataset to study the above aspects for two MNOs in Italy, and make the dataset open-source for further investigation.

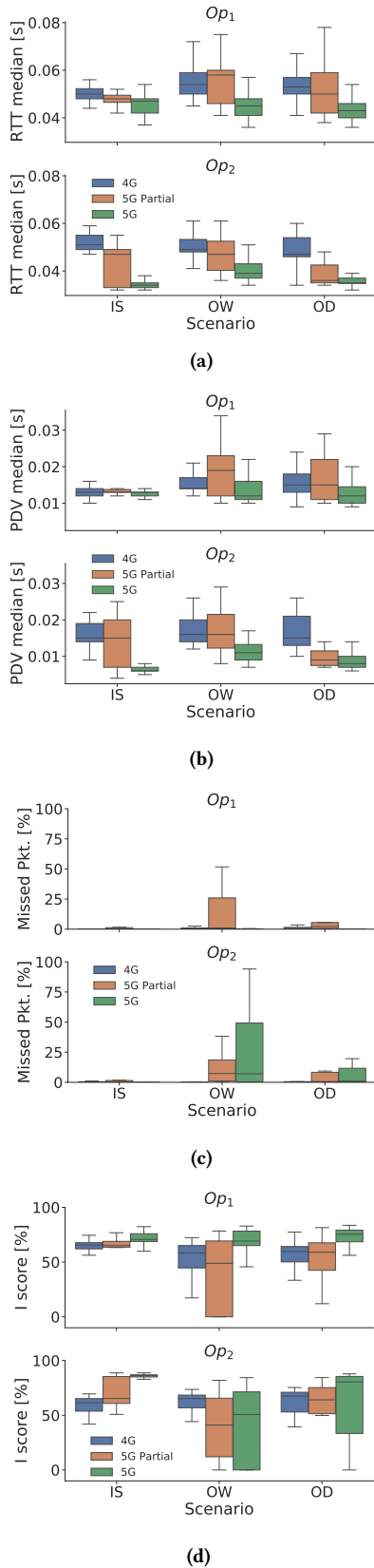


Figure 11: Real-time online gaming application performance grouped by MNO and scenario. (a) shows the median RTT, (b) shows the PDV, (c) shows the missed packet percentage, and (d) shows the i -score.

Results show that disparate 5G NSA deployment strategies by MNOs lead to different radio coverage performance; among others, we observe that SSB beamforming is effective for improving radio coverage. In terms of QoS/QoE performance, 5G provides significant downlink throughput gains compared to 4G, which is a key requirement for eMBB services. From a URLLC latency/reliability perspective, users may also benefit from using 5G NSA, but coverage holes lead to high performance variability and degradation. Overall, 5G gains over 4G are still unstable particularly in scenarios involving mobility, thus requiring further enhancements and optimization of the NSA architecture and corresponding configurations and procedures.

As a future work, we intend to include more application scenarios, such as video streaming in our active measurements analysis. We also plan to conduct more extensive studies on handovers and DC, as well as novel empirical analyses of 5G SA performance.

REFERENCES

- [1] 3GPP. 2018. *5G; System Architecture for the 5G System (Rel-15)*. Technical Specification (TS) 23.501.
- [2] 3GPP. 2018. *NR; Multi-connectivity; Overall Description; Stage 2 (Rel-15)*. Technical Specification (TS) 37.340.
- [3] 3GPP. 2019. *5G; NR; Base Station (BS) Radio Transmission and Reception (Rel-15)*. Technical Specification (TS) 38.300.
- [4] 3GPP. 2020. *NR and NG-RAN Overall Description; Stage 2 (Rel-15)*. Technical Specification (TS) 38.300.
- [5] E. Ali, M. Ismail, R. Nordin, and N. F. Abdullah. 2017. Beamforming Techniques for Massive MIMO Systems in 5G: Overview, Classification, and Trends for Future Research. *Frontiers of Information Technology & Electronic Engineering* 18, 6 (2017), 753–772.
- [6] Usman Ali, Giuseppe Caso, Luca De Nardis, Konstantinos Kousias, Mohammad Rajiullah, Özgü Alay, Marco Neri, Anna Brunstrom, and Maria-Gabriella Di Benedetto. 2022. Data-Driven Analysis of Outdoor-to-Indoor Propagation for 5G Mid-Band Operational Networks. *Future Internet* 14, 8 (2022), 239.
- [7] U. Ali, G. Caso, L. De Nardis, K. Kousias, M. Rajiullah, Ö. Alay, M. Neri, A. Brunstrom, and M.-G. Di Benedetto. 2022. Large-Scale Dataset for the Analysis of Outdoor-to-Indoor Propagation for 5G Mid-Band Operational Networks. *Data* 7, 3 (2022), 34.
- [8] B. Claise and A. Morton. 2009. Packet Delay Variation Applicability Statement. RFC 5481. <https://rfc-editor.org/rfc/rfc5481.txt>
- [9] Konstantinos Kousias, Mohammad Rajiullah, Giuseppe Caso, Ozgu Alay, Anna Brunstrom, Luca De Nardis, Marco Neri, Usman Ali, and Maria-Gabriella Di Benedetto. 2022. Implications of handover events in commercial 5G non-standalone deployments in Rome. In *Proceedings of the ACM SIGCOMM Workshop on 5G and Beyond Network Measurements, Modeling, and Use Cases*. 22–27.
- [10] G. Liu, Y. Huang, Z. Chen, L. Liu, Q. Wang, and N. Li. 2020. 5G Deployment: Standalone vs. Non-Standalone from the Operator Perspective. *IEEE Communications Magazine* 58, 11 (2020), 83–89.
- [11] A. Narayanan, E. Ramadan, J. Carpenter, Q. Liu, Y. Liu, F. Qian, and Z.-L. Zhang. 2020. A First Look at Commercial 5G Performance on Smartphones. In *Proceedings of The Web Conference 2020*. 894–905.
- [12] A. Narayanan, E. Ramadan, R. Mehta, X. Hu, Q. Liu, R. AK Fezeu, U. K. Dayalan, S. Verma, P. Ji, T. Li, et al. 2020. Lumos5G: Mapping and Predicting Commercial mmwave 5G Throughput. In *Proceedings of the ACM Internet Measurement Conference 2020*. 176–193.
- [13] A. Narayanan, X. Zhang, R. Zhu, A. Hassan, S. Jin, X. Zhu, X. Zhang, D. Rybkin, Z. Yang, Z. M. Mao, et al. 2021. A Variegated Look at 5G in the Wild: Performance, Power, and QoE Implications. In *Proceedings of the ACM SIGCOMM 2021 Conference*. 610–625.
- [14] E. Ramadan, A. Narayanan, U. K. Dayalan, R. AK Fezeu, F. Qian, and Z.-L. Zhang. 2021. Case for 5G-aware Video Streaming Applications. In *Proceedings of the ACM SIGCOMM 2021 Workshop on 5G Measurements, Modeling, and Use Cases (5G-MeMU)*. 27–34.
- [15] D. Xu, A. Zhou, X. Zhang, G. Wang, X. Liu, C. An, Y. Shi, L. Liu, and H. Ma. 2020. Understanding Operational 5G: A First Measurement Study on its Coverage, Performance and Energy Consumption. In *Proceedings of the ACM SIGCOMM 2020 Conference*. 479–494.