An Initial Look into the Performance Evolution of 5G Non-Standalone Networks

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Abstract—**Fifth Generation (5G) networks have been operational worldwide for a couple of years. To reveal how the 5G system evolution (e.g., changes in network conditions, deployment, and configurations) affects user performance, empirical long-term analyses are required. This paper presents preliminary insights from our ongoing large-scale measurement study of the commercial 5G non-standalone (NSA) networks deployed in Rome, Italy. An initial comparison between the measurements in 2020-2021 vs. 2023 shows a decrease in throughput and latency performance, calling for deeper analyses toward understanding the root causes and deriving proper optimization solutions.**

I. Introduction and Background

Compared to fourth generation (4G) systems, e.g, Long Term Evolution-Advanced (LTE-A), fifth generation (5G) systems are expected to satisfy more demanding and heterogeneous quality of service (QoS) requirements, e.g., in terms of throughput, latency, and reliability. This to support different enhanced Mobile Broadband (eMBB), Ultra-Reliable Low Latency Communication (URLLC), and massive Machine-Type Communication (mMTC) use cases.

To support such requirements, the 3rd Generation Partnership Project (3GPP) has standardized 5G non-standalone (NSA) and standalone (SA) deployment modes in Release 15 (Rel-15). Both modes require a 5G New Radio (NR) radio access network (RAN). Then, 5G NSA relies on the existing 4G Core Network (CN), while 5G SA uses its own 5G CN. Currently, the majority of mobile network operators (MNOs) are adopting the NSA mode, which is a more straightforward solution for integrating 5G onto existing 4G deployments. Therefore, it is important to analyze how the use of 5G NSA affects network coverage and user performance by leveraging, for example, a measurement-based approach.

Over the last few years, research has been conducted toward characterizing 5G performance. In [1], the analysis of 5G mid-band networks in China has focused on coverage, throughput, latency, and energy consumption. Similarly, a study on 5G mid-band and high-band networks in the US has been conducted in [2]–[4], where energy consumption and video streaming performance have been investigated.

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Within the above context, our paper presents preliminary insights from our ongoing large-scale measurement study on the commercial 5G mid-band NSA networks deployed in Rome, Italy. It represents one of the first efforts toward a long-term analysis of 5G NSA performance in a European country. Our contributions are as follows: in Section II, we describe our measurement campaign, for which the first collection phase was carried out in 2020-2021 [5], [6], and the second collection phase is ongoing at the time of writing (May 2023), and provide an overview of our dataset. In Section III, we present preliminary analyses of throughput and latency performance, showing how 5G performance is evolving over time. Section IV concludes the paper.

II. Measurement Methodology and Dataset

This section describes our measurement methodology and the corresponding collected dataset.

A. First Collection Phase

The first collection phase took place in Rome, Italy, between December 2020 and January 2021. We used a setup similar to the one shown in Figure 1, which is instead being used during the ongoing second phase, consisting of (i) a radio frequency (RF) antenna, (ii) a Global Positioning System (GPS) antenna for measurement geo-mapping, (iii) the Rohde & Schwarz (R&S) *TSMA6* system (including the R&S *ROMES* software), and (iv) a 5G-capable user equipment (UE) (Samsung S20). The setup allowed to perform both passive network monitoring and active performance tests.

Passive monitoring: we leveraged R&S *TSMA6*, a system composed by an Intel PC (Windows) and a spectrum scanner. Alongside R&S *ROMES*, the scanner detects-and-decodes downlink (DL) control signals from the surrounding base stations of operational 3GPP networks. We monitored four 4G bands, i.e., Bands 1, 3, 7, and 20, one 5G mid-band, i.e., Band n78, and the guard band of Band 20, where the Narrowband Internet of Things (NB-IoT) system is deployed to provide IoT services. 4G and NB-IoT measurements were reported at the Physical Cell ID (PCI) level, where PCI is a cell identifier at the physical layer reusable over the RAN. 5G measurements were instead reported at the Synchronization Signal Block

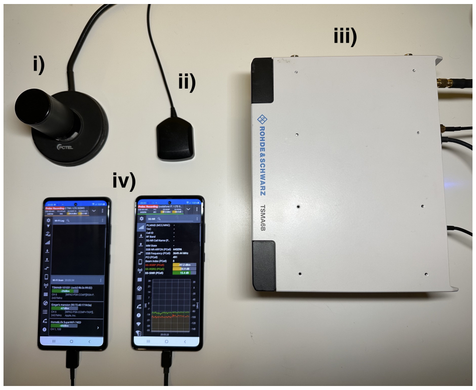

Fig. 1: The measurement setup used for the second collection phase (2023): i) RF antenna, ii) GPS antenna, iii) R&S *TSMA6*, and iv) 5G-capable UEs.

(SSB) level, since 5G PCIs may use SSB beamforming, i.e., signals are transmitted over narrow beams (up to 8 in the mid-band, as per 3GPP Rel-15) to increase spatial diversity and spectrum efficiency.

Active performance tests: we used the UE for executing throughput and latency tests. To assess end-to-end DL and uplink (UL) throughput, we used Ookla Speedtest [7], with a server in Rome.

To assess end-to-end latency, we used the interactivity test provided by the R&S Android app called *Qualipoc* [8] with a server in Switzerland and a traffic pattern mimicking a real-time online gaming service. According to 3GPP, we set a delay budget of 100 ms on the exchanged User Datagram Protocol (UDP) packets; packets not received within the budget were considered lost. Details on both tests are given in [5], [6].

Considering the readiness of 5G networks, we selected two Italian MNOs (Op_1 and Op_2 in the following). Aiming at also comparing 4G and 5G NSA, the UE was configured in either *5G-disabled* mode (only connecting to 4G PCIs) or *5G-enabled* mode (able to connect to 5G and 4G PCIs).

The collection was organized in *sub-campaigns*, carried out in different days/times and according to these scenarios: *indoor static (IS)*, for data mostly collected at different offices of the Department of Information Engineering, Electronics and Telecommunications of Sapienza University of Rome; *outdoor walking (OW)*, for data collected outdoor while walking; and *outdoor driving (OD)*, for data collected outdoor while driving a car. For each sub-campaign, tests were repeated several times; a single test repetition is referred to as a *session* below.

B. Second Collection Phase

At the time of writing (May 2023), the second collection phase is ongoing in Rome, after being kicked-off in March 2023. Most of the configurations of the first phase are being preserved. However, aiming at enriching the analyses, we are extending the collection in different dimensions.

As regards to the setup, we are using a setup similar to that used in the first phase, but we now have two UEs simultaneously connected to *TSMA6* (each one embedded with a SIM card of a different MNO), which makes our collection more time-efficient, since we can perform experiments on up to two MNO networks in parallel. In addition, besides repeating the experiments for Op_1 and Op_2, we are also covering other Italian MNOs that are now providing 5G connectivity in Rome, and plan to test the roaming performance of foreign MNOs.

As regards to the performance tests, Ookla Speedtest is being complemented by a further throughput test compliant to the European Telecommunications Standards Institute (ETSI) specification on the procedure for evaluating the achievable throughput [9]. The comparability between Ookla Speedtest and ETSI test is assured considering that both use multiple Transmission Control Protocol (TCP) flows in parallel to measure the throughput. Moreover, the interactivity test with the online gaming traffic pattern is being complemented by other interactivity tests with different patterns and delay budgets, aiming to analyze the performance of different latency-sensitive services.

As regards to the scenarios, we are refining the OD scenario by taking measurements while driving in urban vs. highway situations. We are also taking measurements in large indoor areas while walking to define an *indoor walking (IW)* scenario.

C. Dataset

The first phase dataset was partly open-sourced along with [5], [6], and completely disclosed and described in [10].

As regards to the dataset collected by the scanner, it includes features that can be grouped in the following classes: spatial and temporal fields, frequency and cell identifiers (e.g., PCIs), and signal strength and quality indicators, i.e., Reference Signal Received Power (RSRP) [dBm], Reference Signal Received Quality (RSRQ) [dB], and Signal to Interference plus Noise Ratio (SINR) [dB]. These are measured on the 4G Reference Signal (RS), NB-IoT RS, and different 5G control signals, for all the PCIs detected by the scanner during each sub-campaign, and particularly for the *serving* PCI, i.e., the one at which the UE was connected.

As regards to the dataset collected by the UE, it includes features that can be grouped in the following classes: spatial and temporal fields, connection and coverage information (e.g., RSRP, RSRQ, and SINR of the serving PCI, as measured by the UE), resource allocation information (e.g., Modulation and Coding Scheme (MCS) and Transport Block Size (TBS)), and performance information (e.g., the throughput at different layers for each throughput test session, and the interactivity score (*Iscore*), defined as a function of round trip time (RTT), packet delay variation (PDV), and packet loss rate (PLR), for each interactivity test session).

III. Results

In this section, we perform an initial analysis of throughput and latency performance observed during the first and second phases by focusing on the 5G NSA network of Op_1 and a specific IS location.

DL throughput: Figure 2 shows some of the time series collected during two 5G-enabled throughput sub-campaigns, for the first (Figure 2a) and the second (Figure 2b) phase,

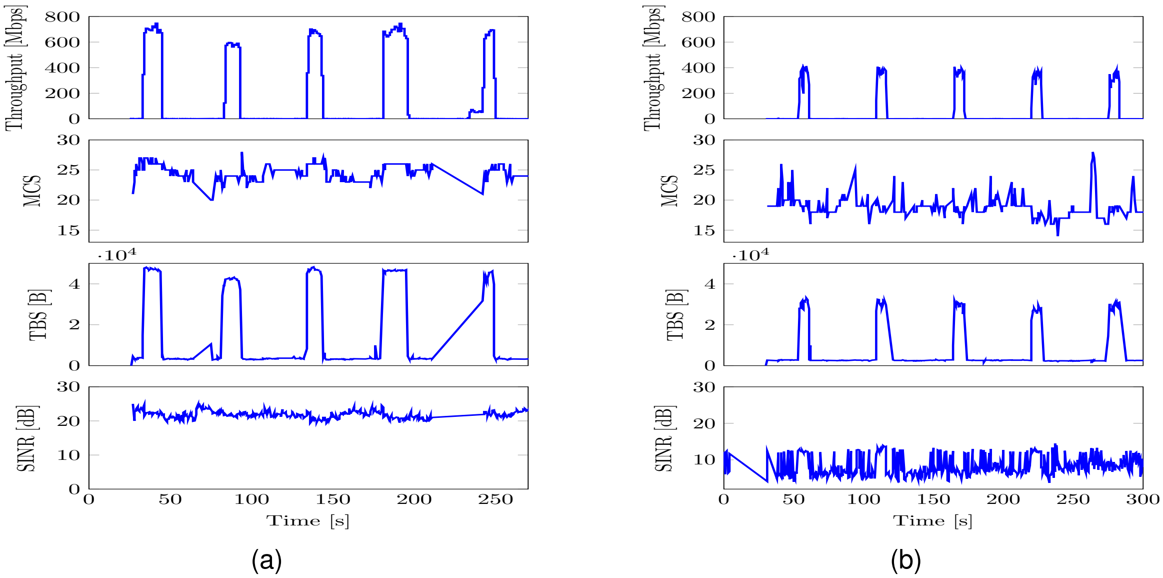

Fig. 2: Application throughput, MCS, TBS and SINR time series collected during two 5G-enabled IS sub-campaigns for Op_1 (same location, 5 sessions each). First (a) vs. second (b) phase.

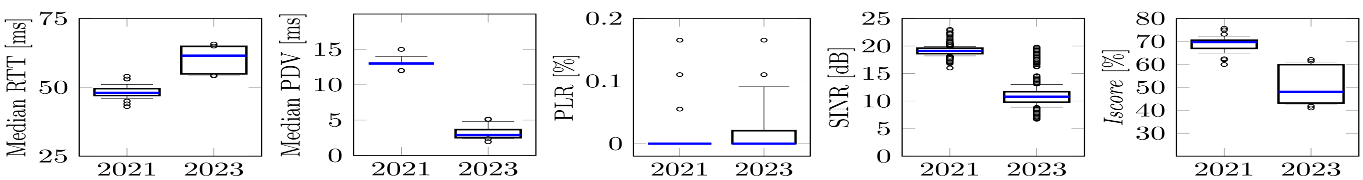

Fig. 3: Statistics in boxplot format (including outliers) of median RTT, median PDV, PLR, SINR, and *Iscore* for the interactivity tests executed during two 5G-enabled IS sub-campaigns for Op_1 (same location). 2021: first phase, 2023: second phase.

respectively. During the first phase, the DL throughput was of about 700 Mbps in most of the sessions (first subfigure), with an MCS index stably higher than 20 thanks to good radio conditions (SINR higher than 20 dB, fourth subfigure). High MCS led to a TBS of around 50000 Bytes (third subfigure) that, when transported in a Transmission Time Interval (TTI) of 0.5 ms (a sub-carrier spacing of 30 kHz is adopted by Op_1), resulted into the observed throughput. During the second phase, a lower throughput was measured, with a value of about 400 Mbps in most of the sessions. This is due to a smaller TBS (around 30000 Bytes), which is in turn due to lower MCS indexes (sporadically higher than 20) and worse radio conditions. As regards to these latter, although the UE is connected to the same PCI of the first phase, the SINR is dropped to around 10 dB, and RSRP/RSRQ are also lower by a couple of dBs each on average (the time series are not reported due to space constraints). This may be a result of multiple factors, including different configurations (e.g., lower PCI/SSB transmission power) and additional interference created by more 5G active users and PCIs in the location surroundings, which may altogether concur to explain the observed lower RSRP, RSRQ, and SINR values. These initial results highlight the importance of better understanding how the network evolution impacts user performance, and motivate our ongoing deeper investigation on the collected measurements, toward deriving long-term network optimization solutions.

Latency: Figure 3 shows some of the statistics collected during two 5G-enabled interactivity sub-campaigns, for the first (2021) and the second (2023) phase. As for the throughput case, a performance decrease is observed in the second phase, with the median *Iscore* (evaluated over several sessions) dropping from around 70% to around 50% (right subfigure). This is due to a higher median RTT (left subfigure), which impacts the *Iscore* more significantly than the decreased median PDV values (middle-left subfigure). Across collection phases, PLR remains very low (middle subfigure), while the lower SNR (middle-right subfigure) confirms the worse radio conditions observed in the throughput test. The results again motivate our ongoing further investigation toward better understanding and proposing solutions for performance improvement.

IV. Conclusions

In this paper, we presented preliminary insights from our measurement study on the commercial 5G NSA networks deployed in Rome, Italy, toward revealing how the 5G evolution affects user performance. An initial comparison between measurements collected two years apart showed clear performance decrease, potentially caused by different adopted configurations and increased interference due to higher network usage. As we progress with the measurements, we plan in-depth analyses toward disclosing the impact of several factors on performance and deriving optimization solutions.

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