# 5G NSA Performance: A Measurement Study

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***Abstract*—5G cellular technology has been widely deployed in several countries by multiple operators in the form of non-standalone (NSA) networks. These networks rely on the 4G control plane and switch to 5G's New Radio (NR) technology for use plane traffic on the radio access, while the transport network is the same as 4G's. Several promising use cases have been showcased, some on top of these commercial networks. However, there is still limited understanding of NR performance in the wild.**

**In this paper, we measure the 5G NR throughput on a 5G NSA base station on campus using a COTS mobile device instrumented with a radio access protocol analyzer. We show that 5G NR user throughput reaches almost 1 Gbps, meeting enhanced broadband expectations. We observe that throughput performance for 5G NR suffers strongly from non-line-of-sight conditions. Further, we analyze throughput differences when there is walking movement when compared to static measurements. We identify unexpected behavior in 5G NR at one location, similar to other 5G performance studies. our results also hint at potential 5G NR rate adaptation inefficiency.**

***Index Terms*—Mobile Network Measurement, 5G New Radio, Throughput, Physical Layer, Application Performance.**

## I. INTRODUCTION

5G New Radio (NR) is a new radio access technology developed by 3GPP for the 5th generation mobile network [1]. It was designed to be the global standard for the air interface of 5G networks [2]. A 10-fold increase in user data rate compared to 4G is one of the main expected improvements of enhanced Mobile Broadband (eMBB), according to ITU-R M.2083-0 [3]. 5G deployments are recent and focus on the eMBB service. The most widely deployed technology is not full 5G, but non-standalone (NSA) 5G. 5G NSA uses the 4G/ LTE control plane to exchange control messages and 5G NR for user plane data on the radio access network (RAN). However, there are currently few assessments of the throughput that such commercial deployments deliver.

In this paper, we used a commercial base station (BS) operating in mid-band (3.6 GHz) to characterize the 5G NSA downlink eMBB service. We use the Packet Data Convergence Protocol (PDCP) throughput as a Key Performance Indicator, the main metric of interest. Specifically, we want to understand to which extent commercial 5G is delivering the promised throughput, and how it changes in the face of different propagation conditions. Further, we look at the impacts of the physical environment on that throughput, and compare relevant changes with respect to 4G using measurements in similar conditions of a co-located 4G base station. The main contributions of this paper are:

- We characterize 5G NR PDCP throughput for a commercial 5G NSA deployment in the wild.
- We explain variations in throughput performance using physical layer indicators (SS-RSRP, SS-RSRQ, MCS, BLER, PUSCH Tx Power) that reflect the impact of different propagation environments on 5G NR mid-band.
- We identify unexpected wireless behavior at a specific position, similarly to [17], [20], and describe it with physical layer indicators.
- We report different behaviour when downloading from different servers, and show that Ookla Speedtest overestimates throughput performance.

The rest of the paper is organized as follows: in the next section we provide some background useful to understand the metrics used in the performance evaluation; in Section III we describe the experimental setting and procedure; Section IV presents the results and reasons about the causes of observed behaviors. Finally, Section V reviews related work, and Section VI concludes the paper.

## II. BACKGROUND: CELLULAR LOWER LAYER METRICS

We will use the throughput as the KPI for 5G service performance. Additionally, we use other observable physical layer indicators to understand and explain what we observe, namely received signal power, received signal quality (which considers the relation of signal power to interference and noise), block error rate, and modulation and coding scheme. In this section, we define precisely how these metrics are calculated from the received frames. We will use 4G performance as additional explanatory variables, so, in the following, we explain also the calculation of metrics for the 4G radio interface.

Figure 1 represents a downlink radio frame [13]. The wireless frames are segmented into Resource Elements (RE), the smallest units that represent one symbol per subcarrier. These REs form Resource Blocks (RB), each comprising 12 consecutive sub-carriers in the frequency domain. Cell-specific Reference Signals (CRS) are embedded within REs, serving as part of Reference Signals designed to uniquely identify

This work is a result of projects FLOYD (POCI-01-0247-FEDER-045912), funded by FEDER through COMPETE 2020, Project Route 25 with Nr. C645463824-00000063, supported by the European Union / Next Generation EU through PRR, and by Portuguese National Funds (OE), through Fundação para a Ciência e Tecnologia, I.P.; and UIDB/50008/2020, funded by the applicable financial framework (FCT/MCTES, PIDDAC). We want to thank Vodafone for the support and useful discussions.


ISBN: 978-3-903176-61-4



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ISBN: 978-3-903176-61-4

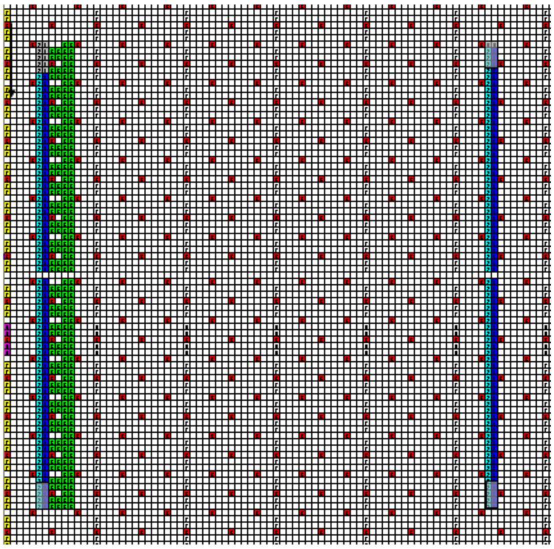

Fig. 1: Downlink Radio Frames

White: Physical Downlink Shared Channel
Red: Resource Elements
Blue: Synchronization Signals
Sky Blue: Secondary Synchronization Signals
Green: Master Information Block
All colors: RSSI

the associated cell. The white blocks represent the Physical Downlink Shared Channel (PDSCH), over which user data is sent.

*a) Packet Data Convergence Protocol Downlink Throughput:* Packet Data Convergence Protocol sits at the top of the radio stack and is the first layer below IP [12]. It adds the PDCP header to the incoming data and forwards it to Radio Link Control (RLC) in the downlink. This layer provides cellular data service to the IP layer, thus PLDPC throughput is the KPI of this study. PDCP Throughput measures the amount of Bytes transmitted in a specified time interval.

*b) Reference Signal Received Power (RSRP):* 5G uses SS-RSRP, where SS stands for "Secondary Synchronization Signal". The User Equipment (UE) uses SS signals to get the necessary information to access a cell, such as time and frequency. "SS-RSRP is characterized as the linear average over the power contributions (in [W]) of the resource elements that carry secondary synchronization signals." [7]. In Figure 1, these are the sky blue RB.

4G's RSRP is calculated over a less specific (and larger) set of signals [6]: "RSRP is characterized as the linear average over the power contributions (in [W]) of the resource elements that transport cell-specific reference signals contained within the considered measurement frequency bandwidth". RSRP calculates the average power of REs carrying CRSs across the entire bandwidth. In Figure 1, these are the red RB.

*c) Reference Signal Received Quality (RSRQ):* SS-RSRQ is a carrier-to-interference (C/I) measurement reflecting the quality of the received reference signal for 5G NR. SS-RSRQ is calculated based on the SS-RSSI and the received interference power [7]: "SS-RSRQ is defined as the ratio of N x SS-RSRP / NR carrier RSSI, where N is the number of resource blocks in the NR carrier RSSI measurement bandwidth."

"RSRQ is described as the ratio (N x RSRP)/(E-UTRA carrier RSSI), where N is the number of RBs of the E-UTRA carrier Received Signal Strength Indicator (RSSI) measurement bandwidth. The same set of RB shall be used in the measurements." [6] The RSSI, which is the linear average of the total received power (in [W]). In Figure 1 the RSSI is the total power of all colors and any possible noise or interference in the time-frequency slot. Thus, the RSRQ is the ratio NxRSRP/(E-UTRA carrier RSSI) of the power in the white squares in the figure over the total power.

*d) Block Error Rate (BLER):* "A Block Error Ratio is defined as the ratio of the number of erroneous blocks received to the total number of blocks sent. An erroneous block is defined as a Transport Block, the cyclic redundancy check (CRC) of which is wrong" [8]. A transport block (TB) is defined as the data delivered by the MAC layer to the physical layer and vice versa. Transport blocks are delivered once every Transmission Time Interval (TTI) [9]. It is the payload that is transmitted over the air interface, while the RB are units of resource allocation in the time-frequency grid. Many RBs may be allocated to transmit one TB, depending on factors such as channel conditions, modulation and coding schemes, and data rate requirements.

*e) Modulation and Coding Scheme (MCS):* The MCS is a value that determines the modulation, coding, and number of spatial channels. [11] MCS defines how many useful bits can be transmitted per RE. MCS depends on radio link quality: the better the quality the higher MCS and the more useful data can be transmitted. However, the specific adaptation algorithm is neither standardized nor open, and the adaptation is based on an estimation of the expected received signal for that RB.

## III. Experimental Setting

Here we describe the set of experiments to explore the performance of 5G NR. The gNodeB is a commercial BS installed on campus anchored on a commercial 5G NSA network. The main set of experiments aimed at measuring the PDCP throughput provided by the 5G NSA network to a device connected to a single cell. The measurements were done along a predefined route offering varied propagation conditions and using two movement patterns: static and walking. We collect RSRP, RSRQ, MCS, BLER and PDCP Throughput from 5G NR. Additionally, in separate runs, we collect similar data for 4G/LTE, a well-known technology with well-understood performance, which may help explain the behavior observed with 5G NR. We planned a route that provided both Line-of-Sight (LOS) and Non-Line-of-Sight (NLOS) conditions, and varying scattering, reflection, and diffraction.

### A. 5G NR PDCP Throughput

To characterize 5G NR's performance through different propagation conditions and mobility profiles, we carried out


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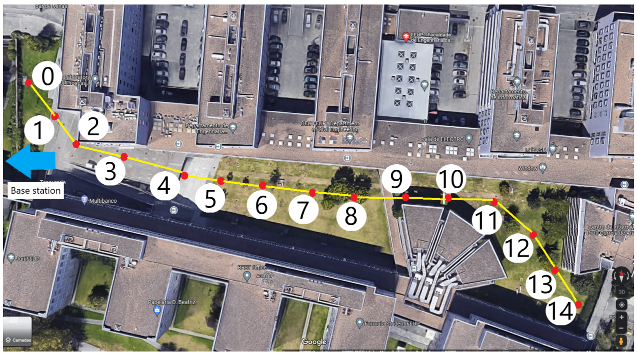


Fig. 2: Route for measurements.

four diverse measurement sessions: 5G NR Static, 5G NR Walking, 4G LTE Static, and 4G LTE Walking. The chosen route was traveled in two ways, discreetly and continuously, for each network technology. One time, the measurements were taken statically at each of 15 points for 10 seconds; another time, the measurements were taken while a person was moving holding the smartphone in front of the body.

*a) Route and Environment:* The chosen route crosses a garden on campus, as depicted in Figure 2. The route lies in front of the main lobe of the BS antenna on the horizontal plane and is thus covered by a single sector. Consequently, there are no handovers in the experiments. The route starts 20 m below the BS in an open area, proceeds to a space between buildings, and then ascends to point PX5 via 15 m wide stairs. The terrain is flat beyond that point. As a consequence, there is a height difference of approximately 4 m between PX0–4 and PX5–11. Points PX2 to PX4 navigate an 18 m wide space between two 4-story buildings without obstructing the LOS. The path between PX4 and PX5 passes under a 2 m concrete bridge, momentarily blocking LOS. Points 5–7 have full LOS to the antenna, while point PX8 encounters trees. These points lie between buildings separated by 20 m, with lawn and few alone-standing trees. The buildings surrounding PX9 and PX10 are only 10 m from one another, experiencing more reflection. Finally, Points 11-14 do not have LOS to the antenna, as they are obstructed by 2-story buildings, but the surrounding buildings are more spaced out (again approximately 20 m).

Concerning propagation phenomena seen in the route, we expect to observe the consequences of the following:

- due to the proximity to the BS and the height difference, points PX0 to PX4 are outside the antenna main lobe on the vertical plane;
- Points PX5 to PX11 were inside the antenna main lobe;
- PX2, PX3, and PX4 are affected by multipath propagation because of the reflection caused by the buildings, which can lead to fading and interference, and they are also likely below the main antenna lobe;
- the path between PX4 and PX5 is affected by the LOS blocking caused by the bridge mentioned above;
- PX5, PX6 and PX7 are in LOS;
- as we continue on the path (PX8, PX9, PX10), LOS gets obstructed by trees, whose leaves and body cause scattering;
- PX9 and PX10 experience stronger multipath effects due to the narrow building spacing;
- PX11 to PX14 have no LOS, and all received signal power reaching the UE comes from the reflection in surrounding or refraction on the blocking buildings;
- all points experience some form of multipath from the surrounding buildings;
- the received signal decreases as the distance to the BS increases due to attenuation.

*b) Tools:* We used a commercial smartphone (Samsung S21) instrumented with a commercial firmware and software package (Infovista TEMS Pocket) that allows us to log physical layer parameters, message exchanges on the link and medium access layers of the protocol stack, and connection and user equipment status. The logs were processed and exported with TEMS Investigation. This device and software require special provisioning by the operator.

*c) Procedure:* To ensure comparable throughput values, the UE started a data session before the beginning of the measurement logging. To guarantee that we were generating sufficient traffic, three test file downloads were ongoing simultaneously throughout the measurement session. The test file consists of Ubuntu Desktop 22.04.2 ISO, found on Ubuntu's website, with a size of 4.6 GB.

Smartphone height relative to the ground was kept constant. Measurements, conducted by the same person, were timed with the phone held at chest height. A cardboard support replicated the chest height for static measurements.

In walking sessions, a constant speed was crucial, with recorded times from start to end. To minimize bias, measurements occurred under similar climatic conditions and when the university had fewer people around, minimizing interference from weather and user equipment.

### B. File Server Impact

We did a second set of experiments to observe the impact of the test file server we used to make the downloads.

*a) Methodology:* The first four tests involved downloading files from various websites on a smartphone using TEMS Pocket. The fifth test utilized a well-known speed test application. All tests were conducted statically at PX6, which benefited from favorable signal conditions within the antenna's main Lobe and open LOS.

*b) Tools:* We used the same smartphone and software as before. We used different test files, selected because of their sizes:

- Ubuntu[1], 4.6 GB: Ubuntu's 22.04.3 ISO for desktops. File used in the first experiment.
- Testfile[2], 5 GB Test file similar to the first one, but hosted on a distinct server.

[1]https://ubuntu.com/download/desktop
[2]https://bit.ly/5GB-TESTFILE-ORG



ISBN: 978-3-903176-61-4

- Centos[3], 9.2 GB: Linux's ISO hosted on FEUP's server.
- Vodafone[4], 1 GB: Test file from a server belonging to the telco that owns the BS used in this experiment.

Finally, we use Ookla's Speedtest. This is an online service used to measure the speed of internet connections. It allows users to test their download speed, upload speed, and ping latency by connecting to a server hosted by Ookla [5].

*c) Procedure:* The setup for this experiment is similar to the previous one. All recordings were made in PX6. However, in this case, the measurement includes the establishment of the data session, i.e. the download starts only after the measurement logging. This allowed us to observe the data session establishment procedure. Also, in this experiment, each recording has a different duration, depending on the time to perform the download.

## IV. Results

### A. Physical Layer Indicators

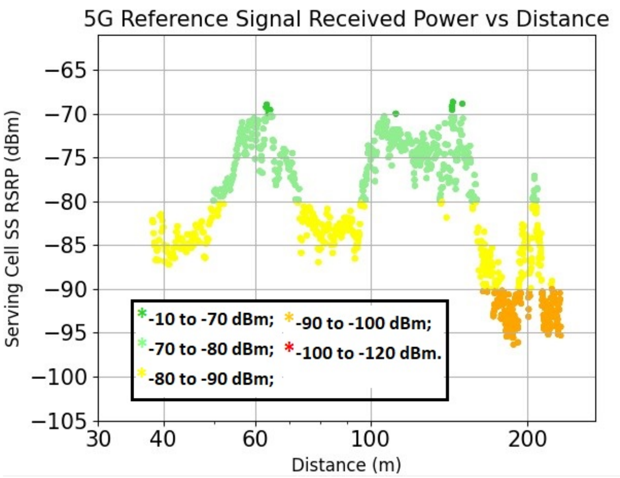


Fig. 3: SS-RSRP vs. Distance

| | | RSRP (dBm) | RSRQ (dB) | SINR (dB) |
|---|---|---|---|---|
| RF Conditions | Excellent | >=-80 | >=-10 | >=20 |
| | Good | -80 to -90 | -10 to -15 | 13 to 20 |
| | Mid Cell | -90 to 100 | -15 to -20 | 0 to 13 |
| | Cell Edge | <=-100 | <-20 | <=0 |

Fig. 4: RSRP and RSRQ reporting range.

*a) Received Signal Power:* Figure 3 displays 5G NR's SS-RSRP vs distance in a moving measurement. Considering the 3GPP-defined RSRP reporting range of -44 to -140 dBm [6], which can be seen in Figure 4, most recorded samples fall within the good or excellent quality range (-70 to -90 dBm), only dipping below these values at the end of the route. Figure 5 shows the projection of the SS-RSRP values on

[3]https://mirrors.fe.up.pt/centos-stream/
[4]http://xcal1.vodafone.co.uk/
[5]https://www.speedtest.net/about


Fig. 5: Route Map

the map of the area. The variations in SS-RSRP correspond to obstacles in the path, as visualized in Figure 2 and reflect the sequence of propagation conditions described in Section III.

Figure 6 shows the evolution of RSRP over distance for static measurements and when walking. SS-RSRP values for PX0 and PX4 are low when compared to the other points with LOS (PX6–PX8), confirming that those points are out of the main vertical lobe. PX5 is an exception that we will discuss below. In the rest of the route, static recordings generally presented better results than their moving counterparts. From PX9 to PX10, the RSRP decreases significantly due to worsening of the propagation conditions. At PX 11, the received signal power increases again more significantly for the static measurements. As propagation conditions worsen, static measurements show better RSRP than walking measurements, reflecting the stronger multipath components with respect ton LOS caused by the narrower building spacing, stronger attenuation and some tree blockage.

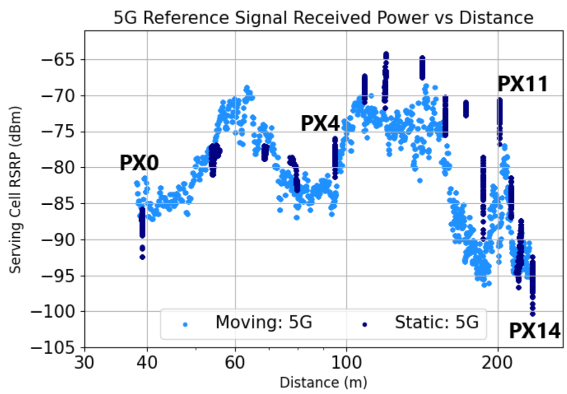


Fig. 6: 5G RSRP vs Distance - Moving and Static.

In Figure 7, we see both 5G NR and 4G LTE RSRP when walking. We see the "M" shape for LTE as we did before for 5G, but the variations are lower. The 5G received power shape is sharper, having lower values when propagation conditions are worse (beginning, middle and end of route), but higher RSRP values in LoS. This reflects the different propagation behavior at the higher frequency band (3.5 GHz for 5G vs 1.8 GHz for LTE) in the first case, and the more powerful radio technology in LoS case.



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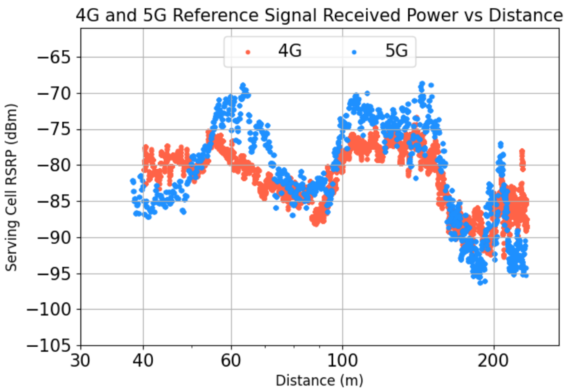


Fig. 7: 4G and 5G RSRP vs Distance - Moving.

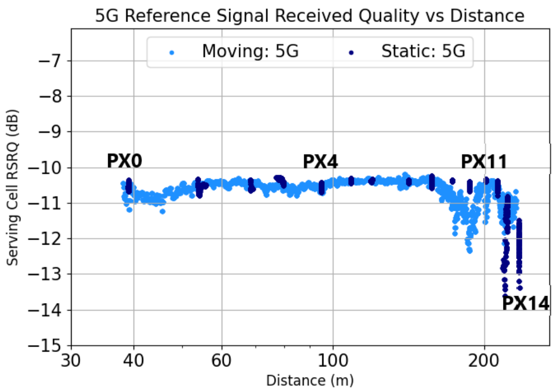


Fig. 8: 5G RSRQ vs Distance - Moving and Static.

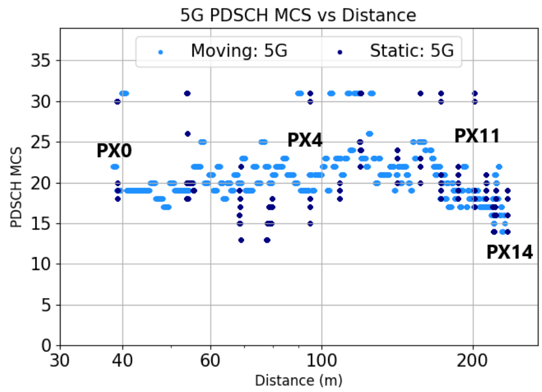


Fig. 9: 5G MCS vs Distance - Moving and Static.

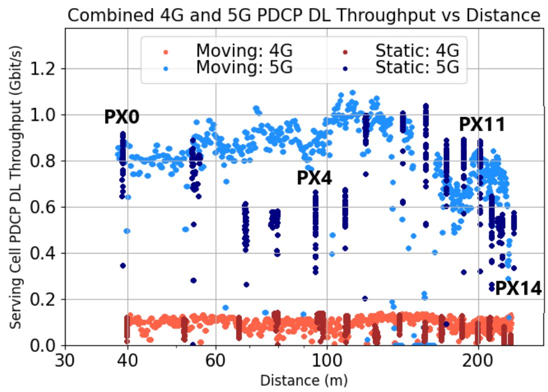


Fig. 10: 4G and 5G Thr vs Distance - Moving and Static.

Figure 8 shows the RSRQ for 5G static and moving patterns. We observe constant quality, as expected due to lack of interference. When the signal quality of the moving measurement decreases near PX9 and 10, the quality of the static measurements stays similar to the previous points, as observed for the RSRP. Finally, at the NLOS points, the static measurements show stronger variation and lower quality values, again reflecting the RSRP, as there is no interference.

*b) MCS:* The MCS variations follow the received signal power variations, as expected. However, we can see lower MCS used for static measurements in PX2-5. Conversely, we observe higher MCS for static measurements in PX9-11, with more frequent choice of high modulation. A factor at play in this difference may be the MCS adaptation algorithm, which may misadapt when moving, as these algorithms are usually reactive to changing conditions.

*c) PDCP Throughput:* Lastly, we display the main KPI—PDCP throughput, in Figure 10. In this case, we present a comparison between 5G NR and 4G LTE to illustrate the difference between both technologies regarding throughput performance.

5G's speed goes up to 1 Gbit/s at its peak throughout the measurements. When the propagation conditions worsen, the throughput decreases to 600–800 Mbps. 5G delivers 8-10 times the throughput observed for 4G under similar propagation conditions. This confirms that at the BS we measured, 5G can deliver its promise of enhanced broadband speed even in uncontrolled measurements with NSA 5G. Although this may seem trivial, it verifies the capability of the technology in the wild and confirms that commercial 5G can deliver on the expectations for eMBB service. When walking, high throughput levels were reached from the beginning and maintained even when SS-RSRP decreased, from points PX2 to PX4, as consequence of higher MCS. Static measurements did not go past 0.6G bps until SS-RSRP improved, from PX6 on. This reflects the lower MCS used, as observed in Figure 9—a consequence of consistent poor received signal. On the other hand, movement allows the device to move quickly out of poor propagation conditions. When the propagation conditions worsen, i.e. the LOS component of the received signal decreases, the behavior becomes the opposite. The static measurements PX9–11 show higher throughput values than the moving measurements in that area. Static measurements also showed higher SS-RSRQ and higher chosen MCS, which explain the higher throughput. We observe MCS 30 and 31 for both static and walking measurements in LoS (PX4-PX6), but we only observe such high MCS for static measurements for NLOS measurements beyond PX8. This may be a consequence




ISBN: 978-3-903176-61-4

of mis-adaptation of data rate when moving in a more complex wireless environment, a well-known effect in wireless data rate adaptation that may be more expressive for the higher data rates. However, this requires confirmation with more detailed measurements. After PX11, no significant difference is seen between the two types of movement.

To conclude, we plotted the relation between SS-RSRP and PDCP throughput for the 5G moving measurements (Figure11). The linear regression shows that the higher throughput speeds were achieved when the SS-RSRP was also high. However, we observe also a variability of around 300 Mbps for a given SS-RSRP, indicating that more complex models with other physical layer indicators are needed to capture this relationship.

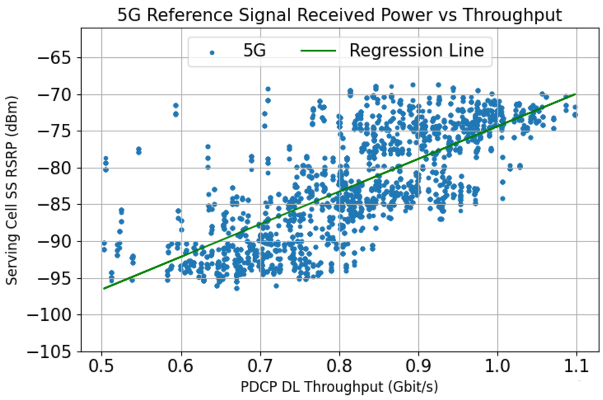


Fig. 11: SS-RSRP vs. 5G PDCP thr - Linear Regression

TABLE I: Regression Coefficients

| | |
|---|---|
| Slope | 1,9266E-06 |
| Intercept | -12,274665 |
| R-squared | 0,401773 |
| Standard Error | 2,6931E-08 |

*d) Unexpected behavior at PX5:* One point caught our attention because its throughput was below expectations: PX5. PX5 is what we thought would be the best position coverage-wise, since it is already inside the main lobe and no physical obstacles disturb the LOS or the 1st Fresnel zone. SS-RSRP values are high in this location for static and moving measurements and there is nothing noticeable about this point with respect to SS-RSRQ or BLER. However, it has low MCS levels compared to other points with similar characteristics, like PX6. We repeated measurements several times at this point, also on different hours and days, and the results were consistent.

We analyzed a different physical layer indicator, the Physical Uplink Shared Channel Transmission Power (PUSCH Tx Pwr). This is the power that the UE should use in uplink transmissions, calculated dynamically to adapt to wireless channel conditions using a factor that depends on channel measurements between the UE and gNB. The calculation procedure is specified in ETSI TS 138 213 [10]. We use it as an additional indicator of the quality of the wireless link between the UE and gNB, since the pathloss estimate is a component in the calculation of this value. Figure 12 shows the relation between throughput and UE PUSCH TxPower for all points of a static route measurement. Once again, PX5's behavior does not fit any of his neighbors', showing throughput that is considerably lower than the other points with similar PUSCH Tx-Power values, like neighboring point PX6. On the other hand, power adaptation should have led to increased transmission power, similar to what we can see for PX2–PX4, which would enable higher MCS. Since this behavior occurred consistently, we conclude that there the wireless link at PX5 is affected by some phenomena that is not reflected in SS-RSRP or SS-RSRQ, but leads to lower than expected MSC (see Figure 9 in comparison with PX6), and consequently to lower than expected throughput. We could not find in deeper log analysis any credible cause for this behavior.

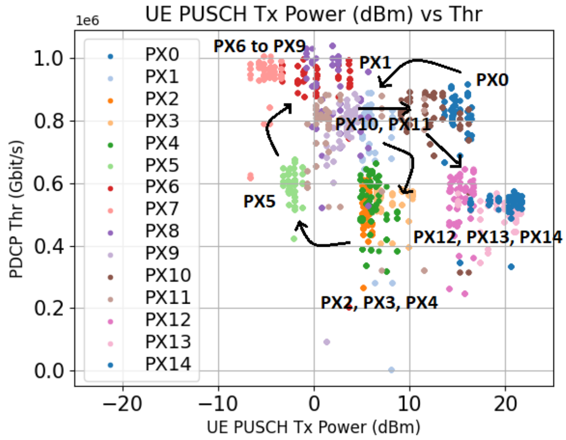


Fig. 12: UE PUSCH Tx-Power vs. Throughput for static measurements

## B. Throughput of Different Servers

One aspect of the static throughput measurements of 5G NR was intriguing. Before settling with the Ubuntu file for the main tests, we downloaded files from diverse servers, resulting in very distinct behaviors of 5G NR throughput. Since radio access is not the single determinant factor for throughput, we explore here the throughbut of different servers measured at PX6.

We plot the variations of the different metrics versus time in Figure 13. The maximum throughput speeds varied largely from file to file. For all of them, throughput decreased abruptly to 4G values at some point, indicating a downgrading of the flow from NR to LTE. Also, we throughput values got close to zero during the measurement at some point. These behaviors were observed for similar download experiments in other points. Since the position, the environment, and the presence of people in the surroundings where each recording was performed were similar, we can exclude these as causes.



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First, we explored the Radio Resource Control (RRC) connection procedure by analysing the messages exchanged between the UE and the gNB. We could relate the ramping up seen at the beginning with a specific message, namely "PDSCH 256QAM In Use". This message confirms that the modulation constellation has changed to 256QAM, marking begin of operation in 5G NR. We could not find any specific pattern to explain the interval between file download begin and switch to 5G.

Even though we could identify the message that triggers the switch from 4G to 5G NR, we could not find any messages or other behavior associated with the steep throughput downfall observed later. When analyzing the SS-RSRP, no considerable variations were seen, excluding this factor as a justification. [6]

Ubuntu and Testfile downloads, despite similar file sizes and indicators, have very different total download times. The Testfile download actually experiences higher SS-RSRP, and similar other indicators, while at the same time lower throughput values. This is extremer for the CentOS download, which sees higher MCS that both previous files. Of course this indicates that the throughput limitation is not caused by the NR link, and highlights the importance of varying servers when measuring 5G throughput performance.

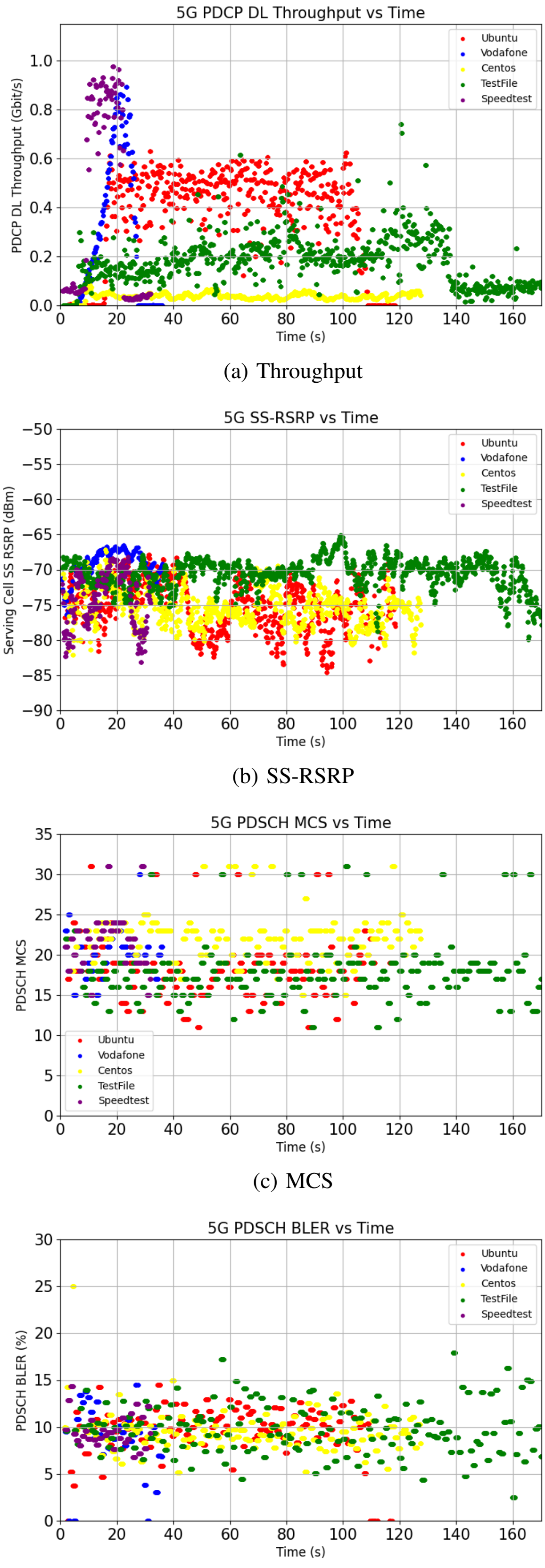
The Vodafone download shows a very slow ramping up to throughput above 900 Mbps, and then a slow decrease. Speedtest, on the other hand, reaches similarly high throughput much faster followed by an abrupt decrease. This highlights that the commonly used tool may overestimate network performance. The performance of the other indicators remains similar for both cases, hinting at other processes in the network or servers as cause.

We observe quite strong variations on MCS, and highlight once more that MCS 30 and 31 occur, though not as often as we expected under the very good propagation conditions. It remains unanswered why we observe so different MCS values in measurements made at the same place under the same conditions. This could hint at ineffectiveness 5G NR table rate adaptation.

## V. Related Work

Narayanan et. al performed stationary tests with clear LOS to the 5G antenna [15], while Rochman [16], Mallikarjun [17] and Xu [20] performed rapidly moving tests in urban settings. Once each research had different goals, many different metrics were used, being SS-RSRP, SS-RSRQ, Throughput speed, and latency the most common ones. Similarly to the first, we chose a very controlled scenario and used a single cell, but we have a more complex and varied propagation environment. Although we measure while moving at walking speeds, staying within a single cell allows us to assess propagation conditions more precisely. Further, our work compares in detail the physical layer parameters (RSRP, RSRQ, MCS, BLER, PUSCH TX-Power) and the PDCP throughput performances of a UE in the same outdoor route.

[6]Also, all SS-RSRQ measurements were practically identical are not shown here.



(a) Throughput

(b) SS-RSRP

(c) MCS

(d) BLER

Fig. 13: Behavior of main metrics for different files.

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Concerning tools, other works also use smartphones and measurement apps [15], [21]. We used TEMS to measure and analyze the physical parameters as an alternative to other applications like ROMES from Rohde and Schwarz [17] or SigCap [16]. Also, the use of PDCP throughput such as Ookla [15] helped us perceive the difference between peak network performance and physical quality metrics.

With respect to the parameters observed, we were influenced by [16] and [21], who compared the throughput speeds of commercial 5G NR to LTE and related the performances to the coverage. We did not make a latency or power consumption analysis with this comparison as in most available works. We focus on displaying the evolution of SS-RSRQ, BLER and MCS and study their behavior regarding the propagation phenomena present along the measurement route.

In many ways, our results regarding throughput performance agree with the values seen in all referenced works. The influence of distance on throughput in our work was expected, as well as the maximum speeds achieved. Also, we experienced similar shadowing and NLOS effects as seen in [16], even though our performance drop was not as severe.

We could not fully explain the behavior seen in PX5, as well as when downloading test files from distinct servers. Mallikarjun [17] and Xu [20] reported similar situations to PX5, where lower throughput speeds were measured with no clear explanation. A more detailed look into this behavior with more precise physical layer equipment is planned as future work. As for the distinct servers, we could not find similar results to ours, for which more tests are also required to better understand the situation.

## VI. Conclusion

This research characterised 5G NR performance in varied outdoor propagation scenarios. We explore how the propagation phenomena impact mid-band frequency's QoS. At the same time, we confirmed that although 5G's full potential is not yet here, commercial 5G can deliver on its enhanced broadband promise. We also unveiled some obstacles that impair the functioning of 5G NR and hint that rate adaptation may be a source of lower-than-expected performance. In future work, we will dig deeper into the causes of unexpected behaviors, and design models for the throughput performance as a function of lower-layer parameters. Improving the rate adaptation mechanism may also be a relevant path to improve throughput performance.

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ISBN: 978-3-903176-61-4