Will the Upper 6 GHz Bands Work for 5G NR? A Urban Field Trial

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ABSTRACT

In the never-ending pursuit of bandwidth, mid-bands have been recently reconsidered as the primary spectrum for 5G NR and its evolution. Laying between the crowded lower frequency bands and the propagation-unfriendly higher bands (i.e., millimeter wave), the upper 6 GHz band (6425-7125 MHz) presents a valuable compromise between capacity and coverage. Recognizing its potential, the research community has expressed interest in this spectrum and conducted several studies. Despite this enthusiasm, the deployment of upper 6 GHz testbeds remains elusive. This paper aims to address this gap by presenting the results of a comprehensive measurement campaign conducted on a 5G NR cellular system operating in the upper 6 GHz band (6425-7125 MHz), specifically deployed within the Politecnico di Milano campus. Our objective was to evaluate the system's performance in a realistic environment and provide insights supported by empirical measurements. The measurement campaign yielded positive results, showcasing a remarkable channel capacity in urban areas, which remained consistently high even at the cell edge and in challenging non-line-of-sight and outdoor-to-indoor scenarios.

CCS CONCEPTS

• **Networks** → **Network experimentation**; **Network measurement**; **Wireless access networks**; **Mobile networks**.

KEYWORDS

5G New Radio, Upper 6 GHz, Enhanced Mobile Broadband, Field trial

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1 INTRODUCTION

The continual increase in the number of mobile users and their bandwidth demands has made the exploration of new spectrum opportunities one of the distinguishing features of mobile radio network advancements in the last decades [10]. In this race to higher and higher frequencies, we met millimeter wave (mmWave) communications in FR2 in 3rd Generation Partnership Project (3GPP) Release 16 [9]. They are an abundant source of underutilized spectrum, with huge bandwidths and very high throughputs, but characterized by harsh propagation conditions [3, 8].

In this panorama, a new band of frequencies has started to gain momentum in recent years. Within the largely utilized mid-band spectrum (1 GHz–6 GHz), the frequency range 5.925-7.125 GHz, known as the 6 GHz band, has become one of the most promising opportunities for mobile communications. Indeed, it has the typical good coverage capabilities of the mid-band spectrum, reduces the hardware complexity required by resorting to higher and higher frequencies, and can provide sufficiently large bandwidths to guarantee gigabits-per-second throughput to mobile users. Given this positive trade-off and the fact that the 6 GHz band occupies a position in the spectrum close to bands typically used by both WLAN and mobile radio networks, the regulatory entities of both systems have started to consider this band for their operations. This has led to the introduction of the upper 6 GHz band among New Radio (NR) bands in 3GPP Release 17 and, in parallel, to the birth of Wi-Fi 6E within the Wi-Fi Alliance, both promising great experiences for mobile or fixed/nomadic users (Wi-Fi being fixed/nomadic only).

This dual interest of WLAN and mobile radio networks in the 6 GHz spectrum must face the type of spectrum access characterizing the two systems. While WLANs operate with unlicensed spectrum, 3GPP systems rely on licensed spectrum. The licensed vs. unlicensed option has generated a large worldwide debate on the topic, considering positive

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and negative aspects from both a technical and a socioeconomic perspective [2]. There is much expectation about the next ITU World Radiocommunication Conference 2023 (WRC-23) that is called to discuss this option from November 20 to December 15 in Dubai. As Administrations worldwide recognize the role that spectrum policy has in addressing climate change, a recent study [5] has estimated the impact on the carbon emissions that the availability of the upper 6 GHz band would have on 5G NR mobile networks and on Wi-Fi deployments addressing future connectivity targets by 2030.

We believe that, as in any engineering discussion, there is a need for experiments and results to understand the benefits and challenges of the alternatives under investigation. Pursuing this objective, we have deployed a 5G NR-compliant mobile radio network testbed operating in the upper 6 GHz band on the premises of Politecnico di Milano campus, aiming to understand its achievable performance. In our trial, the first in Europe and one of the first in the world to conduct a real and extensive measurement campaign, we evaluated radio signal and throughput performance in the urban area of Milan, one of the biggest European metropolitan cities. We have tested outdoor and indoor scenarios and both Line of Sight (LoS) and Non-Line of Sight (NLoS) conditions. This allowed us to draw important conclusions about the viability of the upper 6 GHz band for the 5G NR eMBB use case in urban-macro settings.

The rest of the paper is structured as follows: In Sec. 2, we provide some background on the path of the upper 6 GHz band in the 5G NR specifications, from the first consideration to the standardization. The setup of our upper 6 GHz 5G NR testbed is described in Sec. 3, while field-trail results and their discussion are reported in Sec. 4. Sec. 5 concludes the paper with final remarks.

2 UPPER 6 GHZ BAND FOR 5G NR

5G NR networks and their advancements are envisioned to be used in an increasing number of application scenarios, demanding more and more spectrum. Within the mid-band frequency range, the 6 GHz band stands out as the most promising option to address the need for both coverage and capacity. Consequently, it offers a new spectrum resource that holds significant potential for the long-term development of 5G NR.

This has led to a feasibility study on 6 GHz for Long Term Evolution (LTE) and NR operations that were approved at 3GPP TSG RAN meeting #79 in March 2018. This band, specifically the frequency range 5.925-7.125 GHz, is primarily allocated to mobile services at the international level. At the World Radiocommunication Conference 2019 (WRC-19), several regions and countries proposed to establish the study of the 5.925-7.125 GHz frequency band and dedicate portions of it for mobile telecommunications use. In addition, a first discussion has emerged about leaving the lower band (5.925–6.425 GHz) for unlicensed use and considering the upper band (6.425–7.125 GHz) for licensed mobile services.

Based on this large public discussion, policymakers and spectrum regulatory entities have started to approve the first 6-GHz recommendations. In the USA, the US Federal Communications Commission (FCC) in April 2020 adopted rules that made the full 1,200 MHz of spectrum in the 6 GHz band (5.925–7.125 GHz) available for unlicensed use [4], partially for low-power indoor use, and the majority under an Automated Frequency Coordinator (AFC) framework for unlicensed use. These rules were immediately adopted by the Wi-Fi community as Wi-Fi-6E, promising unprecedented experiences for Wi-Fi users. In Europe, the EU Commission Implementing Decision of June 2021 [12] states that 5.945–6.425 GHz frequencies can be used by unlicensed wireless access systems subject to specific EIRP limitations and an adequate spectrum sharing mechanism that makes the spectrum available on a non-exclusive, non-interference, and non-protected basis.

The discussion on 6 GHz has continued in preparation of the Mobile World Congress 2023 (MWC 23), where participants highlighted that the availability of this band is crucial for achieving digital and green transitions and utilizing both the lower and upper parts of the band can provide the necessary capacity and coverage for different services [7]. Considerations about the split allocation have emerged as well, where the lower part is designated for Wi-Fi and the upper part is identified for International Mobile Telecommunication (IMT), in order to meet the capacity and data speed requirements of both Wi-Fi and IMT technologies. They discussed the importance of balancing different services, considering environmental impacts, and achieving global harmonization in spectrum allocation decisions. The forthcoming World Radiocommunication Conference 2023 (WRC-23) is expected to play a pivotal role in securing the future of public mobile networks by discussing the necessary steps to be taken to establish a solid foundation for 5G NR and its evolution within this spectrum range. At the end of 2022, in Europe, the RSPG (Radio spectrum policy group, the high advisory body of the European Commission) adopted its Opinion on the WRC-23, which recommends that "the EU position should be to accept an IMT identification at WRC-23, while not advocating for it or proactively supporting it" under certain conditions [11]. Also, very recently, China's

Figure 1: Aerial view of the test area with 5G NR equipment details.

Ministry of Industry and Information Technology has formalized the identification of the upper 6 GHz band (or portions thereof) for IMT systems, including 5G/6G[1].

Unlicensed NR use has been standardized in 3GPP Release 16 within the spectrum range of 5.925–7.125 GHz, while during the 3GPP RAN#96 plenary meeting in June 2022, the upper 6-GHz (U6G) spectrum (6.425–7.125 GHz) was included in 3GPP Release 17 as an IMT licensed band for NR, numbered as band n104. The RF specifications for both network infrastructure and user equipment were approved by 3GPP, establishing a standardized foundation for the industry to develop products that utilize this spectrum. Although 5N NR licensed system has not been implemented on this band, the results we show in the following are to provide examples of how 5G NR licensed system can be used on 6 GHz frequency band and what its achievable Key Performance Indicators (KPIs) are.

3 TESTBED AND METHODOLOGY

In October 2022, Politecnico di Milano obtained a temporary exclusive licence from MISE [2] to experiment in the upper 6 GHz band using a testbed fully compliant with 5G NR standard. The main components of the testbed are shown in Figure 1. An Active Antenna Unit (AAU) has been mounted on the rooftop of a campus building and connected to a Baseband Unit (BBU) through 25Gbps fiber fronthaul. A 10Gbps backhaul is then used to connect the BBU with a server for traffic generation. The so-composed Base Station (BS) provides 5G NR Standalone (SA) connectivity to a Test UE (TUE) consisting of a commercial smartphone chassis hosting the onmidirectional antenna and RF components, a BBU, a server for traffic generation, and a battery. The TUE equipment is housed inside a small cart with wheels to emulate a mobile user. Only one TUE was realized for this experiment. Specifications and protocol parameters of the testbed are reported in Table 1.

Frequency range	6425 ÷ 7125 MHz (n104)
Channel bandwidth	80 MHz
Center frequency	6800 MHz
Subcarrier spacing	30 kHz
Frame structure	TDD 4:1 (DDDSU)
Maximum modulation	256 QAM
AAU Tx ower	37 dBm
AAU antenna gain	33 dBi
AAU EIRP	70 dBm
AAU MIMO	128T-128R
TUE EIRP	22 dBm
TUE MIMO	2T-4R
TUE radiation pattern	Omnidirectional

Table 1: Hardware specifications and 5G NR parameters

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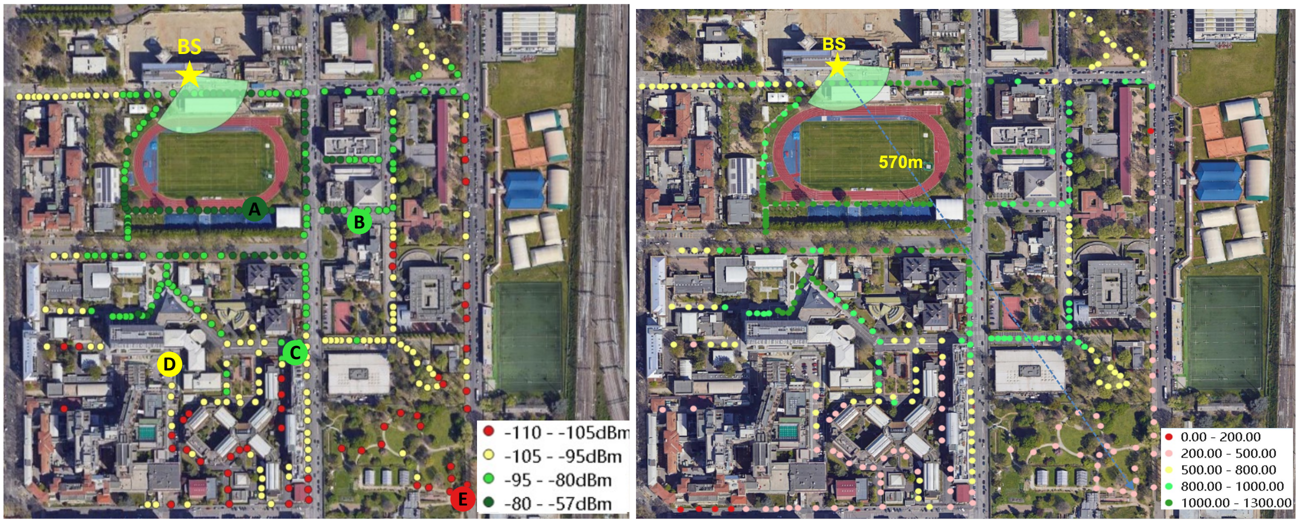
[1] https://www.miit.gov.cn/jgsj/wgj/gzdt/art/2023/art_92c8962a03a44a37becc2963cb3c8df9.html

[2] Ministry of economic development



(a) Outdoor downlink RSRP map **(b) Outdoor downlink throughput map**

Figure 2: Outdoor downlink Reference Signal Received Power (RSRP) and throughput measurements.

The test area is urban, with parks, foliage, and relatively tall buildings. The average building height is around 20 meters, with the tallest construction being measured at 40 meters. Measurements have been conducted assuming a cell radius of around 570 m. Figure 1 shows a view of the test area highlighting the AAU installed on a building rooftop at 22 meters height approximately, down tilted by 2° and covering a 120° sector with its center 135° in azimuth. This urban area allows testing diverse scenarios. For example, the stadium's grandstand in front of the AAU is 9 meters tall and creates an NLoS urban canyon scenario along the street right below the building where the AAU is installed. Furthermore, the abundance of buildings in the vicinity also allows experimenting Outdoor-to-Indoor propagation conditions, along with more traditional LoS and NLoS conditions. The measurement campaign was conducted in October over a duration of three days, from morning to evening.

4 RESULTS

This section contains a comprehensive collection of results taken from the field trial. In particular, we will show the performance of the upper 6 GHz 5th generation (5G) NR deployment in outdoor and indoor settings by evaluating the RSRP, uplink/downlink throughput (measured at the application layer), and active Modulation and Coding Scheme (MCS) statistics.

4.1 Outdoor-to-outdoor performance

TP	Dist.	LoS	DL TP	UL TP	Rank (D/L)
A	175 m	yes	1282 Mbps	132 Mbps	4/2
B	236 m	no	992 Mbps	95 Mbps	4/2
C	310 m	no	770 Mbps	55 Mbps	4/2
D	344 m	no	550 Mbps	12 Mbps	3/1
E	570 m	no	332 Mbps	6 Mbps	2/1

Table 2: Specific test point details and measurements.

We begin by showing the downlink RSRP as measured by the TUE in the walkable outdoor part of the test area. Figure 2a shows the measurements overlayed on the aerial view of the test area. Here it is possible to notice that the test points in LoS with the BS receive the highest RSRP, as expected. At the same time, it appears that NLoS conditions do not necessarily incur into low RSRP. Indeed, relatively high RSRP has been measured even in test points where the LoS was obstructed by only one building. However, with multiple buildings blocking the LoS, performance decreases sharply even in relatively close proximity to the BS. Furthermore, we observe a *street-canyon* effect that increases the received signal strength to relatively high values even with multiple blockages and up to the cell edge. We correlate the RSRP values with the peak downlink throughput measured at the same test points, whose values are overlayed on the test area in Figure 2b. Here it is shown how, even where the signal strength is at its lowest, the peak supported throughput remains well above 200 Mbps. We refer to Figure 3 for a more detailed analysis. Here we plot the empirical Cumulative Distribution Functions (CDFs) of the measured RSRP and throughput. Results show how a RSRP of -110 dBm, a typical

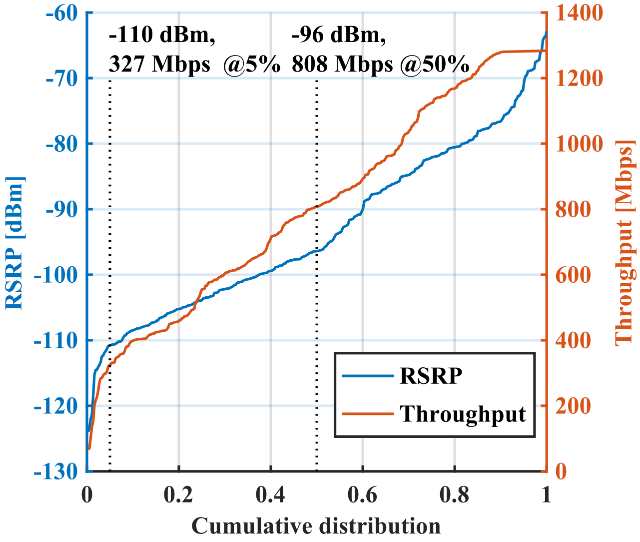


Figure 3: Empirical CDFs of RSRP and throughput.

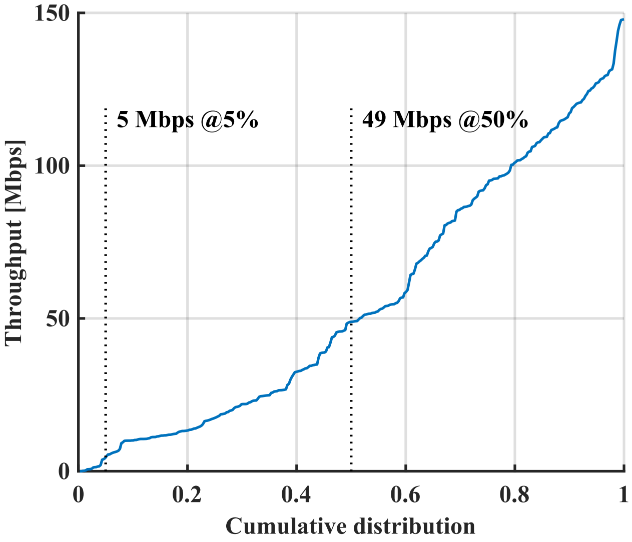


Figure 4: Empirical CDF of uplink throughput.

value at the cell edge and for strong blockage, still can support a peak throughput of around 330 Mbps. Furthermore, these values have been measured for no more than 5% of the test points. Finally, 50% of the test points receive a peak throughput of more than 800 Mbps.

As for the uplink performance, we point to Figure 4, where the empirical CDF of the measured uplink throughput is plotted. We observed lower uplink throughput values with respect to downlink. This was expected, and it is due to several factors. One is the unfavorable Time Division Duplexing (TDD) radio of 4:1. Additionally, the MIMO capabilities of

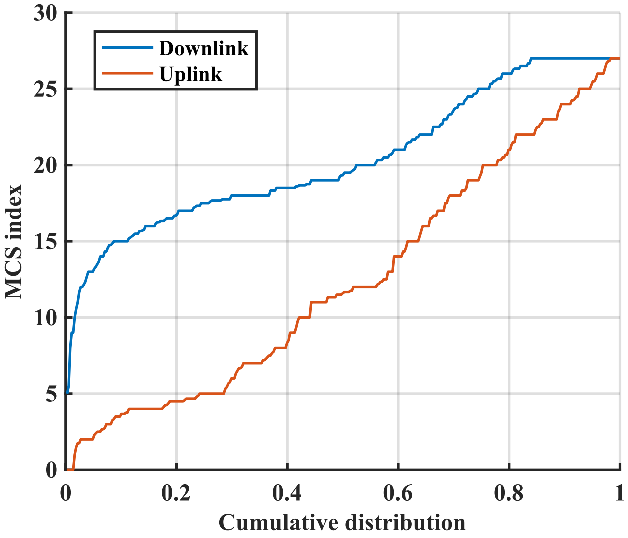


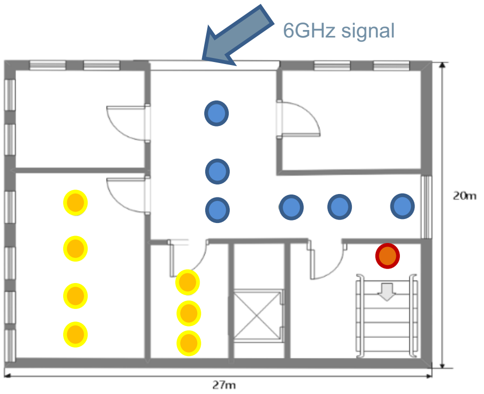
Figure 5: Empirical CDF of downlink and uplink active MCS.

the TUE are lower in uplink, as shown in Table 1. Finally, the lower TUE transmit power also decreases the uplink performance. This is evident in Figure 5, where we have plotted the empirical CDFs of the active MCS index, both in downlink and uplink. As the uplink transmission power is low, the RSRP is also reduced, and the supported MCS index is always lower than the downlink direction.

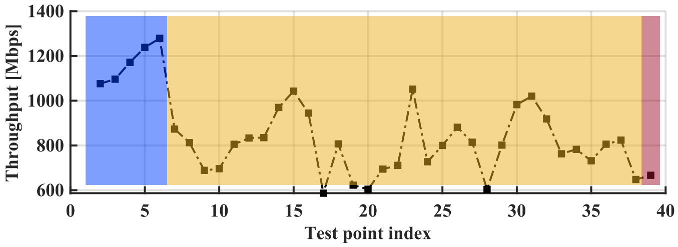
Overall, the system shows uplink performance degradation with particularly unfavorable propagation characteristics. This experiment suggests using higher transmission power and additional MIMO layers for User Equipments (UEs), which is often impractical due to the power consumption constraints of mobile terminals. Nevertheless, applications where these constraints do not apply, such as 5G NR Fixed wireless access (FWA), have the potential to benefit from increased uplink transmission power and MIMO capabilities, thereby mitigating this effect. Alternatively, utilizing frame structures that prioritize the uplink can offset the decrease in spectral efficiency, potentially through the implementation of dynamic TDD techniques to prevent unnecessary degradation in downlink performance [6].

We conclude this part of the analysis by giving a more detailed recollection of the system performance in a set of discrete scenarios. These correspond to selected test points, highlighted in Figure 2a, which exhibit particularly interesting and diverse characteristics from the propagation environment standpoint. The test point details and the measurements are summarized in Table 2.

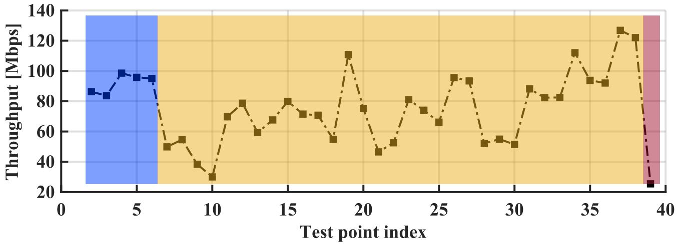
We begin with test point A. It is placed in LoS with the base station at a short distance of 175 m and, as such, it represents



(a) Test points inside the building.



(b) Downlink throughput.



(c) Uplink throughput.

Figure 6: O2I measurements. Blue, yellow and red denote test points in the lobby, rooms with windows and rooms without windows, respectively.

one of the test points with the most favorable propagation conditions. Here the downlink throughput is 1282 Mbps with a channel rank (i.e., number of obtainable independent data streams) of 4, and the uplink throughput is 132 Mbps with a channel rank of 2. The performance experienced at this test point sets the benchmark for the upper 6 GHz 5G NR deployment of this study. Indeed, these values are around 80% of the peak MAC throughput computed according to [1] and thus consistent with the expected overhead.

We now compare this benchmark with increasingly more challenging scenarios.

Test point B is placed slightly farther than A, at 236 m. However, it is not anymore in LoS, as it is blocked by a single building. In this case, the downlink and uplink throughput values decrease between 20% and 25% of the benchmark, reaching 992 Mbps and 95 Mbps, respectively. The channel rank stays full in both directions. This represents the typical performance degradation experienced when a single building blocks the LoS and it is consistent with other test points presenting the same propagation characteristics.

Test points C and D are at a comparable distance from the base station: around 330 m. Furthermore, the LoS is blocked by 2 buildings for both test points. However, they experience significantly different performances due to the *urban canion* effect. Test point C is located on a road flanked by buildings and its measured performances are 770 Mbps and 55 Mbps for downlink and uplink, respectively, with no channel rank decrease. On the other hand, test point D is located in a *cul-de-sac* and cannot benefit from the same *urban-canion* effect. Indeed, the measured throughput here is 550 Mbps in downlink and 12 Mbps in uplink, with both channel ranks decreased by 1. This specific instance gives a numerical quantification of the effect of the building layout, which was generally consistent throughout the entire measurement campaign.

We conclude by detailing the performance measured at test point E. This is located at the cell edge, 570 m away from the BS, and the LoS is obstructed by multiple buildings. Furthermore, it is located in a park, so no strong *urban-canion* effect is present in this case. Ultimately, this is an instance of one of the less favorable propagation scenarios. The measured performance here is 332 Mbps for the downlink throughput and 6 Mbps for the uplink throughput, with channel ranks reduced to 2 and 1, respectively. While the peak downlink data rate might still support most applications, the uplink data rate appears to be suffering the most, as already mentioned in the general analysis.

4.2 Outdoor-to-indoor performance

To characterize the Outdoor-to-indoor (O2I) performance, we have conducted a similar analysis inside a building highlighted in Figure 1. This building is located in LoS with the BS at a distance of around 200 m. The downlink and uplink throughput just outside of the building measures around 1200 Mbps and 130 Mbps.

Figure 6a reports a key set of test points overlaid on the building plan of the first floor. Test points in blue are scattered in the lobby, where a large glass window is in direct LoS with the BS. These test points are subject to the best propagation characteristics, as the electromagnetic waves have to penetrate only the glass windows. Consequently, both downlink and uplink perform well, as shown in Figures 6b and 6c, stabilizing on average values close to those measured outside of the premise and confirming a good glass penetration capability.

Test points in yellow in Figure 6a are located in those rooms of the floor which do not have any glass window in LoS with the BS. However, these still have windows overlooking the streets surrounding the building, which allow for the radio signals to reach the TUE with relatively high strength through reflection and other propagation effects. Indeed, Figures 6b and 6c show how the throughput decreases mildly.

Figure 6a reports in red the test point located in a rooms with no windows. In other words, the radio signal has to penetrate concrete walls to reach these points. Here Figures 6b and 6c show a significant decrease in performance, with the downlink throughput being reduced by half and the uplink throughput by around 80% in the worst case. Similarly to the previous analysis, the uplink performance is more sensitive to particularly harsh propagation conditions. Still, the system shows overall good O2I performance.

Finally, while the yellow and red test points are located at similar depths inside the building, the former benefit from higher performance thanks to the signal penetrating the windows even in NLoS.

5 CONCLUSION

This paper presents the results of a measurement campaign conducted on a mid-band 5G NR cellular network operating in the upper 6 GHz frequency portion. The study involved deploying a 5G NR base station on the rooftop of a tall building in an urbanized area and characterizing the system performance in a real environment.

We observed that downlink channel capacity peaked at 1.3 Gbps under LoS conditions. High performances were also maintained in NLoS scenarios, with a capacity exceeding 800 Mbps on average and 200 Mbps at the cell edge. In NLoS situations, the presence of urban canyons helped maintain good channel quality, while more challenging NLoS cases, such as areas surrounded by tall buildings or difficult outdoor-to-indoor, resulted in decreased performance. Similar results were found for the uplink direction, which however appears to be more sensitive to harsh propagation conditions.

Overall, the measurements presented in the paper demonstrate that mid-band cellular networks offer a favorable trade-off between performance and coverage.

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