Outdoor-to-Indoor Performance Analysis of a Commercial Deployment of 5G mmWave

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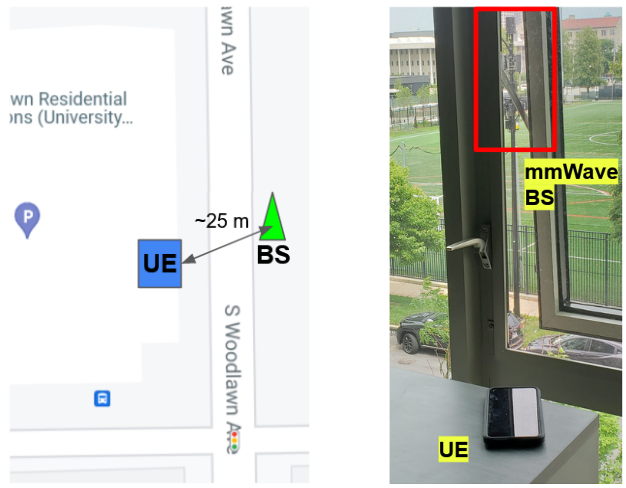
***Abstract*—While millimeter wave (mmWave) channel modeling and propagation studies using channel sounders have been carried out for many years, the performance of commercially deployed 5G mmWave cellular networks has only recently begun to be thoroughly evaluated, mostly in outdoor environments. A recent measurement study [1] predicted outdoor-to-indoor (OtI) mmWave downlink throughputs of 500 Mbps - 2.5 Gbps based on measurements using channel sounders, not with measurements on deployed networks and consumer devices. In this paper, we report the *first detailed OtI measurements of commercially deployed 5G mmWave using consumer handsets* in a location in Chicago where a Verizon 5G mmWave base-station (BS) is deployed across the street about 25m from an university dormitory. Our detailed indoor measurements of uplink (UL) and downlink (DL) throughput and latency contradict the results in [1] and demonstrate that OtI 5G mmWave reception is extremely variable: maximum DL throughput of about 1.8 Gbps is obtained only in a very small number of locations where the user equipment (UE) is line-of-sight (LoS) to the BS through an *open window*. In general, the 5G mmWave connection performed better than low-band 5G in terms of DL throughput. However for UL throughput and latency, the UE performed better when connected to low-band 5G under non-LoS (NLoS) conditions compared to 5G mmWave. Furthermore, when the windows are shut, *i.e.,* there is no Verizon 5G mmWave reception indoors, we observed better OtI DL throughput from mid-band 5G deployed by T-Mobile compared to Verizon 5G NR in the low band. Thus on overall, there is only an extremely small advantage in performance from OtI 5G mmWave reception compared to low and mid-band 5G.**

***Index Terms*—5G, mmWave, throughput, latency, indoor, measurements.**

I. Introduction

Mobile wireless applications are moving beyond the needs of traditional consumer wireless: applications such as AR/VR and enterprise deployments in warehouses, parking lots and university campuses create different demands on cellular networks in terms of latency, jitter, packet drop ratio, coverage, and capacity. The recent deployments of 5G New Radio (NR) in low (< 1 GHz), mid ($1-6$ GHz), and high (> 24 GHz) bands serve these different demands in terms of coverage, range, and capacity. Frequency Range 1 (FR1) denotes the sub-6 GHz frequency range of NR and serves the needs of low to medium capacity links with longer range while the NR high-band/mmWave, denoted as Frequency Range 2 (FR2) is



(a) BS and UE location. (b) LoS between BS and UE.

Fig. 1: Outdoor-to-indoor (OtI) measurement location.

used for the higher capacity needs in the Gbps range but with shorter range. In addition to direct connections between base-stations (BS) and user equipment (UE), another emerging use of 5G mmWave is in apartments and enterprises as an alternate backhaul solution for supporting indoor Wi-Fi networks which are also capable of supporting Gbps throughput using the latest 802.11ax standard in the newly unlicensed 6 GHz band. In order to enable such "hot-spot" type applications, the 5G mmWave receiver needs to be either placed outside with line-of-sight (LoS) to the BS, leading to higher installation cost, or indoors for a simplified and lower cost deployment: however the outdoor-to-indoor (OtI) propagation limitations may reduce the performance of the latter. While there are many *theoretical and simulation* studies of indoor-only and OtI mmWave performance [2], [3], [4], there are very few *measurement* studies on OtI performance, especially on *deployed 5G mmWave networks.*. A recent paper [1] presented results on OtI performance using custom channel sounding equipment and predicted downlink (DL) throughput of 500 Mbps - 2.5 Gbps depending on the type of glass used in windows. However, these measurements were not conducted over deployed 5G mmWave networks and were not using consumer devices.

In this work, we present the first OtI 5G mmWave performance results from measurements conducted in realistic

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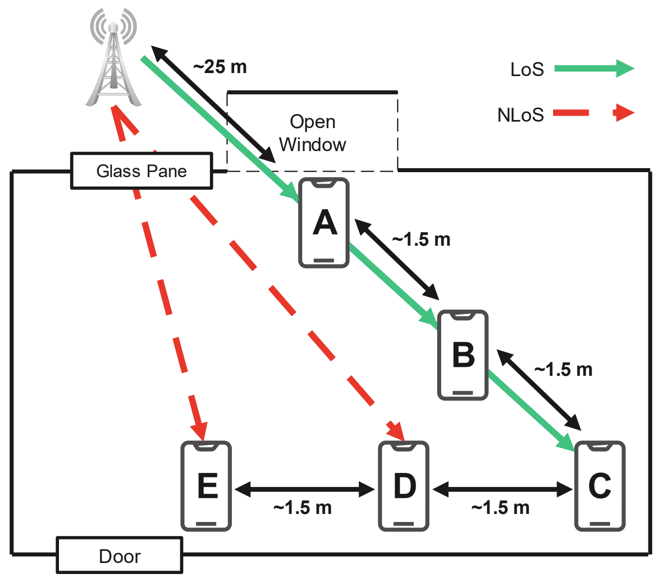
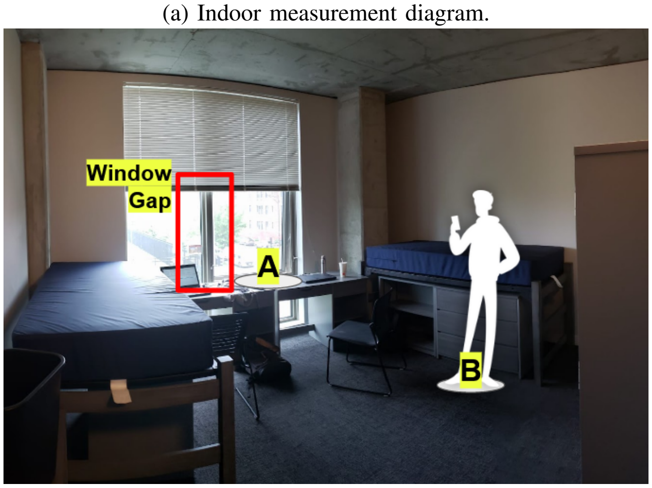


(a) Indoor measurement diagram.



(b) Indoor measurement picture.

Fig. 2: Indoor measurement scenario.

environments using commercial deployments and consumer devices. The experiments were conducted at an University of Chicago dormitory building where a Verizon base station is deployed across the street, approximately 25 m away as shown in Fig. 1. We analyzed the performance of an indoor UE placed in various locations within rooms, as shown in Fig. 2, and on different floors, in terms of the downlink (DL) throughput, uplink (UL) throughput, and round trip latency. In addition to quantifying Verizon 5G mmWave performance, we also compared performance with Verizon 5G in the low-band (Verizon 5G C-band was not deployed in this location at the time these experiments were conducted), AT&T 5G in the low-band and T-Mobile 5G in the low and mid-bands. Table I summarizes the various operators and the 5G and 4G frequency bands and bandwidths that were observed in the indoor locations tested: Verizon was the only operator with 5G mmWave reception indoors (on band n261 at 28 GHz). Our main conclusion from the extensive measurements we performed is that while significant DL throughputs of up to 1.8 Gbps can be received in a very small number of indoor locations where the UE is close to the window and the window is fully open, in the majority of indoor locations the device falls back to 4G and low-band 5G when the window opening is reduced or fully closed and the device is not in unobstructed LoS to the BS. Thus, sustained OtI 5G mmWave reception indoors will continue to be a significant limitation on performance of 5G mmWave.

TABLE I: Indoor Cellular Reception at UChicago Dormitory. SA: standalone, NSA: non-standalone

Operator	**5G NR Mode**	**5G NR Band (Max. Bandwidth)**	**4G LTE Band (Max. bandwidth)**
AT&T	NSA	n5, 850 MHz (5 MHz)	2 (15 MHz), 12 (10 MHz), 14 (10 MHz), 17 (10 MHz), 30 (10 MHz), 66 (10 MHz)
T-Mobile	NSA	n41, 2.5 GHz (100 MHz), n71, 600 MHz (20 MHz)	2 (15 MHz), 66 (15 MHz)
Verizon	NSA	n5, 850 MHz (10 MHz), **n261, 28 GHz (400 MHz)**	2 (5 MHz), 13 (10 MHz), 66 (20 MHz)

II. Related Work

With the increasing number of 5G mmWave deployments in many cities, the emphasis is shifting to quantifying 5G mmWave performance using commercial deployments and UEs. Recent literature [5], [6], [7] has demonstrated the feasibility of achieving very high throughput with consumer smartphones over commercially deployed 5G mmWave, in spite of the well-known limitations of mmWave propagation due to beam tracking, beam management, mobility management and building blockage. Advanced techniques, based on machine learning and artificial intelligence, have been proposed for addressing these limitations, for example in [8], [9]. Most recently, [10] presents detailed measurements of 5G mmWave deployments by two major commercial 5G operators in the US in diverse environments using smartphone-based tools. Similar studies focused on UL throughput of 5G mmWave were reported in [11]. In other recent work [12], it was demonstrated that it is a challenge to sustain prolonged high DL throughput over 5G mmWave due to the rising skin temperature of the UE, which is influenced by the number of mmWave channels, location of mmWave antenna inside the UE, CPU usage, and ambient temperature. As the skin temperature threshold is breached, the UE reduces the number of mmWave channels being aggregated from 4 to 1 *i.e.,* from 400 MHz to 100 MHz, with further temperature rise leading to handover to 4G LTE, thus degrading the throughput from Gbps to Mbps in a short span of time (in the order of tens of seconds). Note that the above results were all obtained from measurements conducted in *outdoor* environments.

Recently, the authors of [1] performed a rigorous and thorough measurement campaign focused on the OtI scenario in different environments concluding that a user can achieve a maximum of 2.5 Gbps DL throughput in 90% of indoor locations with a link distance of up to 68 m. However, these conclusions are based on measurements using continuous wave channel sounders and non-commercial UEs, where the antenna placement and orientation can be quite different from those on commercial devices. Further, the throughput predictions were based on measured signal strengths, not on actual data transmission, since the experiments were conducted using channel sounders.

Our work in this paper reports the first results from OtI measurements in a location where an outdoor 5G mmWave installation by Verizon could be leveraged for detailed indoor measurements in a dormitory building in close proximity. Our measurement results, using a deployed network and commercial devices, offers a different conclusion from [1] regarding achievable throughput indoors from outdoor 5G mmWave: >1 Gbps DL throughput on 5G mmWave can only be sustained if the UE is LoS with the BS and the window is open. We note that our measurements were carried out in a newer building with Low-E glass windows. Since we did not have access to other indoor locations in close proximity to a deployed 5G mmWave BS, we were unable to compare performance with different types of glass as was done in [1].

III. Measurement Tools and Methodology

In order to measure indoor performance of 5G mmWave served by an outdoor BS, we located a 5G mmWave BS 25m from an University of Chicago dormitory building, Woodlawn Residential Commons, at 1156 E 61st St, as shown in Fig. 1a. Construction of this building started in 2018 and completed in 2020, and though we were unable to confirm the type of glass used in the windows, we believe that given the very recent construction of the building, the windows most likely use Low-E glass. The measurements reported in this paper were conducted in July 2021 when we obtained special permission from the university to conduct measurements indoors in various rooms.

We used a number of Google Pixel 5 phones as UEs, with the Android 11 operating system and unlimited data plans with no throttling of 5G mmWave data, along with a number of measurement apps described below.

- **SigCap** [5], [13]: an Android app developed at the University of Chicago which collects time and location information along with signal and network parameters (*e.g.,* 4G and 5G RSRP, RSRQ, RSSI, PCI, 4G frequency, etc) every 10 seconds. Signal data is collected through APIs that extract the information directly from the modem chip and hence is compliant to relevant standards.
- **FCC Speed Test (FCC ST)**: developed by SamKnows for the US Federal Communications Commission (FCC) for the purpose of a nation-wide mobile network survey. For each speedtest, the app performs downlink and uplink throughput tests (over 5 seconds) and an end-to-end latency test. While the data from each test is automatically uploaded to the FCC server, it can also be extracted directly from the phone for analysis. Multiple different speedtest servers are used in different locations: we confirmed that all tests reported in this paper connected to the speedtest server at Chicago, thus enabling accurate comparisons of latency results.
- **Network Signal Guru (NSG)**: a commercially available measurement app that utilizes the phone's root capability to provide more detailed information about transmission parameters such as operating frequency, number of carrier components, bandwidth, Resource Block (RB) allocation, PHY throughput, and RRC (Network layer) messaging. However, exporting information out of NSG requires time-consuming and laborious manual processing of recorded data and hence we use NSG judiciously for targeted analysis.

Fig. 2 shows the different UE locations inside the room with respect to the BS and window placement. The window could not be fully opened: it could be cranked outwards to create a small gap as shown in Fig. 1b. Adjacent to the window is a fixed plane of glass that cannot be opened at all. The UE locations are labelled as A to E from the closest (A) to the farthest (E) from the window. Unobstructed LoS to the BS through the open window was available only at locations A, B, and C, while locations D and E were NLoS through the open window even though the BS was directly visible from these locations through the glass pane. Fig. 2b also illustrates the measurement methodology, with the UE placed on a table at location A, and held at waist level at locations B, C, D, and E (locations C, D, and E are omitted in Fig. 2b for brevity). SigCap and NSG were run in the background to collect detailed signal parameters while the FCC ST was run over several minutes at each location, collecting downlink, uplink and latency measurements. 5G mmWave reception was only available in a limited set of rooms facing the BS on different floors: E206, E306, E406, E506 and E606 on floors 2 - 6 respectively. 5G mmWave was not received on the 7th floor.

IV. 5G Deployment Details

Preliminary measurements showed a number of different 4G LTE and 5G NR signals that were received inside the building from deployed AT&T, T-Mobile, and Verizon in different bands, using both standalone (SA) and non-standalone (NSA) modes, as summarized in Table I. Indoor Verizon 5G mmWave reception in 28 GHz with a maximum bandwidth of 400 MHz using 4-channel aggregation (CA) was possible in some locations. However, the reception was poor, likely due to the Low-E glass used in the windows. There were only a handful of rooms that were LoS to the BS that could receive 5G mmWave signals when the window was open, as shown in Fig. 1b. Also, while this particular Verizon BS was capable of transmitting LTE-LAA in the unlicensed 5 GHz band (band 46) and 4G LTE in the Citizens Broadcast Radio Service band (CBRS, band 48), we did not receive transmissions on these bands indoors, even with windows open, most likely due to the lower transmitted power allowed in these bands.

All Verizon 5G NR deployments were NSA, but there was a difference in the LTE primary channel used depending on the NR band. When NR band n5 (low-band, bandwidth 10 MHz) was used, the LTE primary on the DL was always band 66 with a bandwidth of 20 MHz, whereas when NR band n261 (mmWave) was being used, the LTE primary carrier on the DL was either band 66 or band 13 with a bandwidth of 10 MHz. This difference in choice of LTE primary channel has an effect on overall DL and UL throughput as will be explained in the next section.

V. Experimental Results

A. Performance as a function of floor height

For this set of experiments, the window in each room was set to the maximum possible opening. As shown in Table II, 5G mmWave signals are received with varying average RSRP levels and different beam indices on floors 2 to 6. When a 5G mmWave connection was available, 4 channel aggregation was always used. We also verified using NSG that all available mmWave RBs were allocated to the UE, indicating that there were no other devices connected to the BS during the experiments. We see from Table II that the average RSRP on the 3rd floor is lower than the 2nd, 4th and 5th floors: this could be due to the beam index not being optimally chosen since we also observe that the beam index (20) was the same for the 3rd and 4th floors.

TABLE II: mmWave at Location A on different floors

Floors	Beam Index	Avg. RSRP	Avg. RSRQ
2nd (E206)	4	-94.17 dBm	-11 dB
3rd (E306)	20	-98.57 dBm	-11 dB
4th (E406)	20	-94.36 dBm	-11 dB
5th (E506)	24	-94.48 dBm	-11 dB
6th (E606)	27	-103.99 dBm	-11.67 dB

Fig. 3 shows the DL throughput performance across the floors, in location A (closest, LoS) to E (farthest, NLoS). In floors 2 - 5, there is a degradation of DL throughput as the UE is moved further inside the room, with the worst DL performance in locations D and E where the UE is no longer connected to 5G mmWave but is instead handed over to low-band NR (band n5 850 MHz, 10 MHz bandwidth). In E606 (6th floor), location B performs better than A: this could be because location A is at the edge of the serving beam, or the wider bandwidth LTE primary on band b66 is being used.

Overall, there is a degradation in DL throughput as the UE is moved to the higher floors as well. Each floor is served by a different beam index, except for the 3rd and 4th floors. Fig. 3 shows a lower DL throughput performance at location B in room E406 (4th floor), compared to the 3rd and 5th floors. This indicates a non-optimal choice of serving beam, *i.e.,* the location B of the 4th floor could be a transition area where beam indices 20 and 24 overlap, and the UE may be better served by beam index 24 instead.

Fig. 4 shows the UL throughput performance across the floors. Similar to the DL performance, the UL performance of the UE is degraded as the UE is moved to the higher floors, however, the effect of varying location inside a room is not as straightforward. Best UL performance is mostly seen in location A, except for rooms E506 and E606 (5th and 6th floor), respectively. This indicates that a LoS connection to the BS is not enough to guarantee a good UL performance on the higher floors. This could also be due to the fact that the beam at the UE is much wider compared to the BS since there are fewer antenna elements on the UE. Interestingly, when the UE switches to 5G NR low-band in locations D and E in these rooms, the UL throughput improves compared to when connected to 5G mmWave: this could be due to the wider bandwidth (20 MHz) of the LTE primary channel b66 (band 66) in these locations compared to 10 MHz b13 used with 5G mmWave. Lastly, Fig. 5 shows latency performance across the floors, which shows a reverse pattern to the throughput: lower latency values are obtained in locations D and E where the UE is connected to low-band NR and LTE band b66. This indicates that 5G mmWave transmission incurs additional overheads due to beam management requirements, thus leading to increased latency.

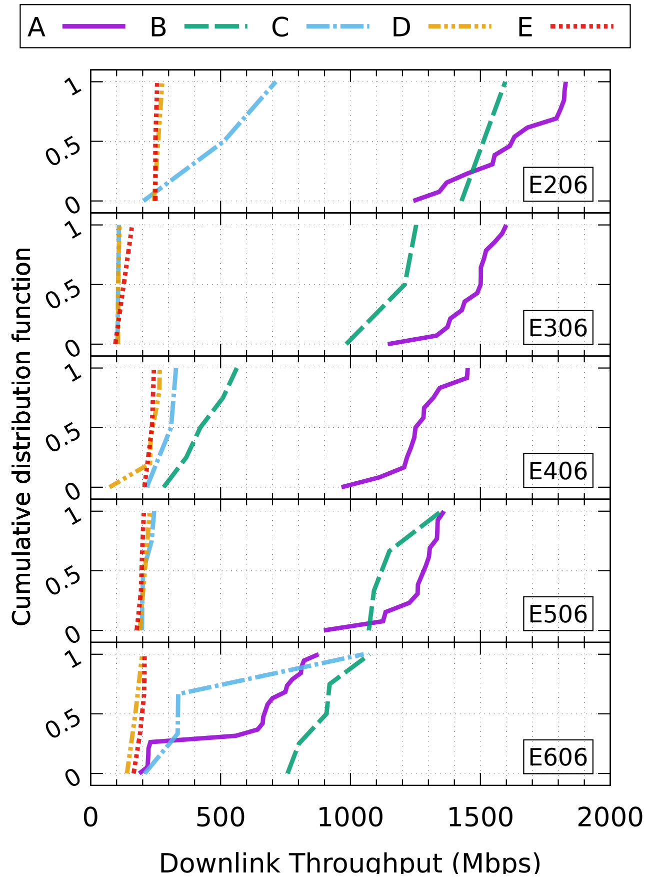


Fig. 3: Downlink throughput performance on all floors.

B. Performance as a function of window opening gap size

The best 5G mmWave performance was obtained in room E206 on the 2nd floor. Hence, we performed additional experiments in this room to quantify performance as a function of

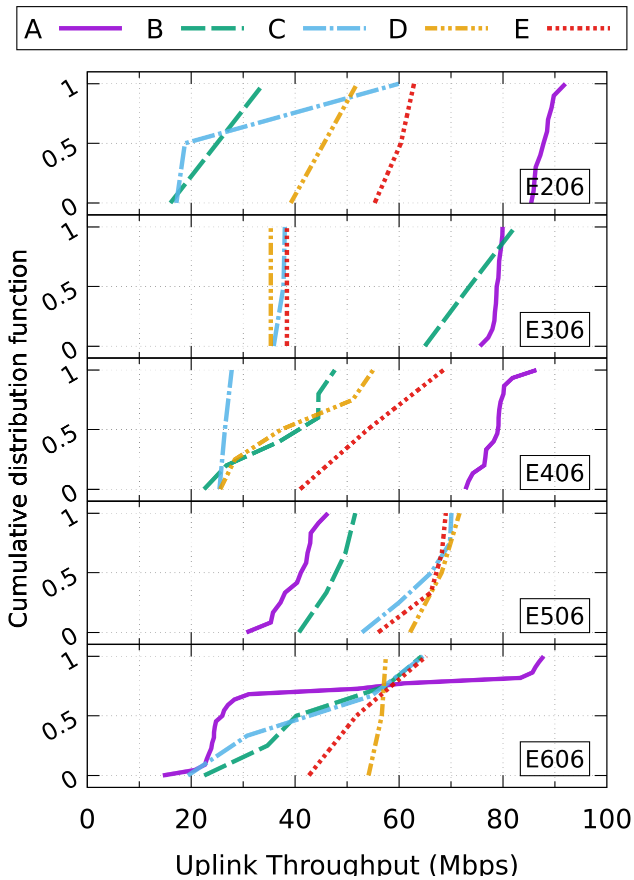


Fig. 4: Uplink throughput performance on all floors.

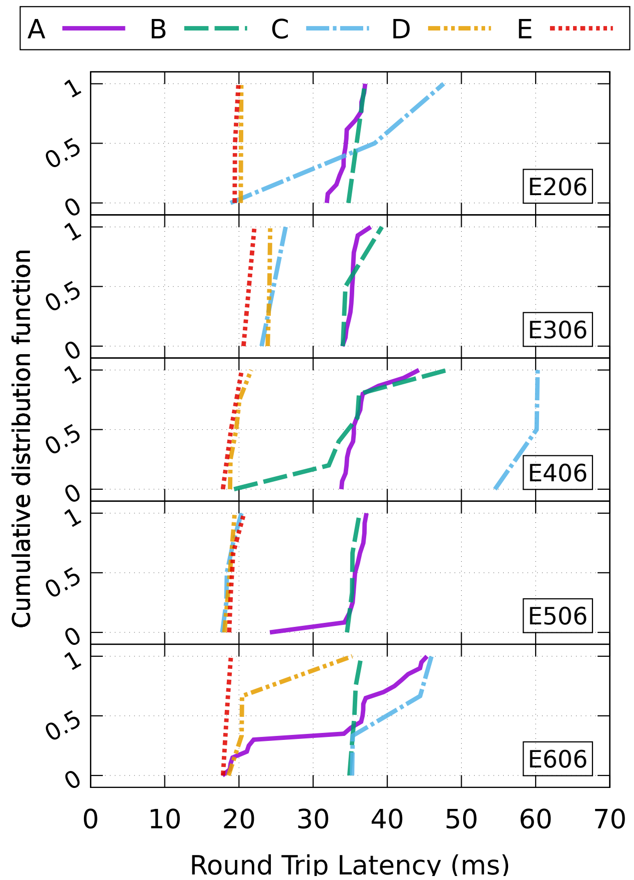


Fig. 5: Latency performance on all floors.

the window opening gap size. The UE was placed in location A and the width of the window opening was varied as shown in Fig. 6, where Gap 1 is the widest gap and Gap 4 is a fully closed window. For each gap setting, measurements were taken over 15 minutes.

Table III shows the comparison of UE performance with different gap sizes. For Gap 1 and Gap 2, the UE was connected to mmWave but the RSRP was almost 10 dB lower in the latter case. When the gap was reduced in the Gap 3 and Gap 4 settings, the UE no longer connects to 5G mmWave at all and instead switches to 5G NR in the low-band and there is not much difference in the RSRP since unlike band n261 at 28 GHz, band n5 at 850 MHz propagates very well indoors and is less dependent on the window gap size.

The throughput and latency performance obtained with the various window gap settings are shown by Fig. 7. There is a significant performance difference between Gap 1-2 and Gap 3-4, due to the difference in the NR band being used. The best DL throughput is achieved with the Gap 1 and 2 settings when connected to 5G mmWave as shown by Fig. 7a. However, the best UL throughput and latency is achieved by Gap 3 and 4, as shown by Fig. 7b and 7c. These results agree with the previous results on different floors and corroborate the conclusion that true Gbps throughput over 5G mmWave can only be delivered indoors when there is unobstructed LoS through an open window.

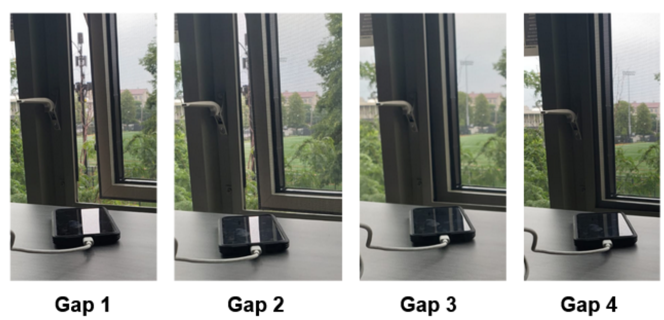


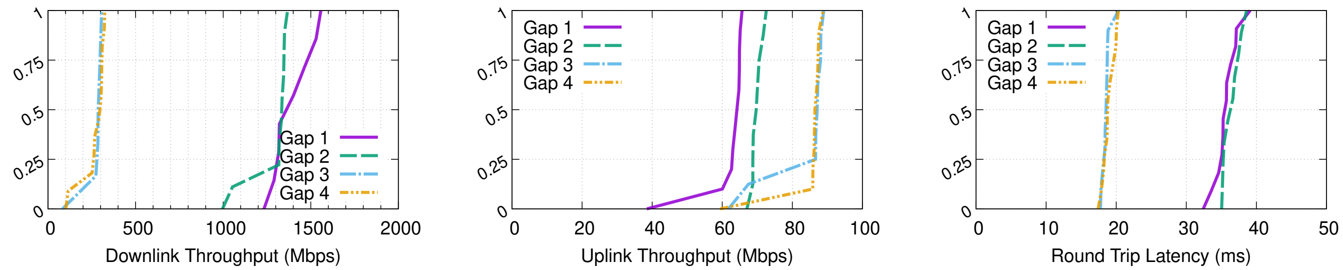
Fig. 6: Window opening gap diagram.

TABLE III: NR Reception on Different Gaps

Gap #	NR Channels	Avg. RSRP	Avg. RSRQ
Gap 1	4 × n261 (400 MHz)	-89.52 dBm	-11 dB
Gap 2	4 × n261 (400 MHz)	-98.98 dBm	-11 dB
Gap 3	1 × n5 (10 MHz)	-74.34 dBm	-11 dB
Gap 4	1 × n5 (10 MHz)	-75.60 dBm	-11 dB

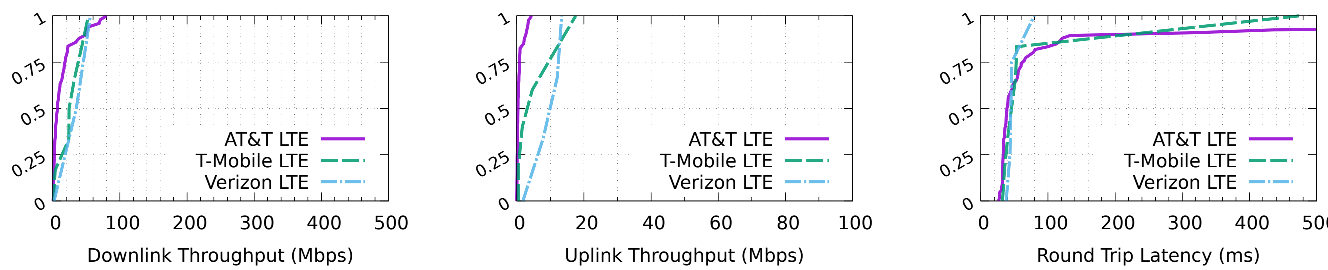
C. Comparison of 5G NR performance among different bands and operators

We surveyed floors 2 - 7 of the building using three identical Google Pixel 5 phones, one for each operator. The phones were placed on a cart and wheeled to different rooms in the building facing the mmWave BS, not just the ones where the detailed measurements were performed. Measurements were taken in

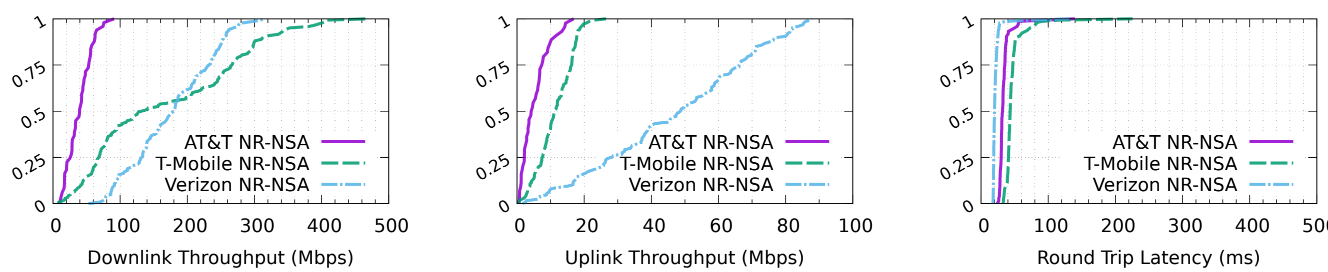


(a) Downlink throughput. (b) Uplink throughput. (c) Round trip latency.

Fig. 7: Throughput and latency performance as a function of window opening size



(a) LTE downlink throughput. (b) LTE uplink throughput. (c) LTE latency.



(d) NR-NSA downlink throughput. (e) NR-NSA uplink throughput. (f) NR-NSA latency.

Fig. 8: Indoor survey of AT&T, T-Mobile, and Verizon in terms of throughput and latency performance.

corridors as well. All windows were shut during this survey. As stated previously, Verizon 5G mmWave was not received at all on the 7th floor, but other bands and operators were, so the results presented in Fig. 8 include measurements on the 7th floor. *Since all windows were shut, no Verizon 5G mmWave was received even in rooms directly facing the mmWave BS.* We also confirmed from our measurements that all Verizon channels in all NR and LTE bands that were received inside the building were being transmitted from the BS on the pole right outside the building. However, we are uncertain about the exact location of the AT&T and T-Mobile BSs.

DL Throughput comparison: From Figs. 8a and 8d we see that NR clearly delivers significant DL throughput improvements over LTE, especially for T-Mobile and Verizon. AT&T NR performance is limited due to the low-band only deployment using only 5 MHz of bandwidth, compared to T-Mobile's 100 MHz at 2.5 GHz and Verizon's 10 MHz. Since Verizon 5G mmwave was not received during these tests, the DL throughput is solely via aggregation of LTE and low-band NR. With no mmWave reception, T-Mobile NR DL throughput is superior to Verizon's, even though the Verizon BS is very close to the building. Once again, this survey demonstrates the severe limitation of indoor 5G mmWave reception.

UL Throughput comparison: From Figs. 8b and 8e we see that here too NR clearly delivers significant UL throughput improvements over LTE, for all operators. There is a clear advantage of Verizon UL, most likely due to the aggregation with the 20 MHz band 66 LTE carrier and the proximity of the location to the BS enabling higher modulation-coding settings. For example, the 80 Mbps throughput is due to 65 Mbps over band 66 and only 15 Mbps over NR band n5.

Latency comparison: From Figs. 8c and 8f we see that there is not an appreciable reduction in latency with NR, though overall Verizon latency with NR is the lowest. However previous results already noted that NR latency was lower in the low-band compared to mmWave, and these results only include low-band NR. It should also be noted that since most of these measurements were over the NSA mode of NR, the latency could be higher due to the dual connectivity, channel aggregation and the use of the 4G core network. As SA with the new 5G core begins to be deployed, we anticipate that the latency results will improve.

VI. Discussion

The closest recent work on OtI mmWave performance that is comparable to ours is [1]. While both papers deal with the performance of OtI mmWave performance, the methodologies employed are very different, leading to different and contradictory conclusions. Our measurements were specifically conducted on deployed 5G mmWave systems using consumer handsets: thus, all real-world conditions such as beam-management using phased-arrays at both BS and UE, wide-bandwidth operation (400 MHz) and handset limitations are included in the performance we measure. Our performance metrics are direct measurements of throughput (uplink and downlink) and latency. Since these measurements were made on a deployed network, they include all overheads due to the MAC, transport and network layers as well. On the other hand, the throughput results reported in [1] are based on predictions from signal strength measurements using a specific channel sounder that utilizes a continuous-wave tone at 28 GHz as the sounding signal, rotating horn antennas on the receiver and omni-directional transmit antennas: very different from actual operating conditions of 5G mmWave. Further, the effects of the intermediate layers are not accounted for in the prediction. These major differences in measurement methodologies and environment lead to the contradictory results: our results demonstrate that in a building with Low-E glass windows located about 25m from a 5G mmWave BS, there is no 5G mmWave connectivity at all through closed windows and limited connectivity in a few locations with the window open whereas the prediction in [1] is of 1.2 Gbps under similar operating conditions in 90% of locations. Additionally, our measurements provide comparison of both throughput and latency performance when 5G NR in the low-band is used instead of 5G mmWave and especially in the case of uplink throughput and latency we demonstrate superior performance of the former due to effective aggregation with the LTE primary channel. Further, we compare performance across different bands and operators to demonstrate that OtI performance over 5G mmWave is unavailable in this building when the windows are shut, but low and mid-band 5G NR can provide DL throughput of up to 400 Mbps.

VII. Conclusions and Future Work

We presented the first in-depth measurement-based analysis of outdoor-to-indoor 5G NR performance in mmWave and other bands over deployed 5G networks using consumer handsets. The results demonstrate that OtI performance over 5G mmWave is severely limited and is available in only very few locations with unobstructed LoS. This is in contrast to recent results presented in [1] which are discussed in detail in the previous section. Further, results presented in our work demonstrate that uplink throughput from indoor devices on low-band NR can exceed that of 5G mmWave NR and that latency on 5G mmWave is higher than low-band 5G. Comparison with other bands and operators also demonstrates that comparable 5G performance can be obtained in the mid-bands, with 100 MHz bandwidth.

Our future work will focus on deeper investigations of the allocation between different LTE and NR bands using newer tools like Qualipoc [14] that allow us to extract detailed network layer information. Since the measurements reported in this paper were performed, all operators have diversified their 5G NR deployments using newer bands and migration to SA modes. Our work also underscores the continued need for performing measurements and experiments on deployed networks with consumer devices to understand 5G NR performance in general and mmWave in particular, under real-world conditions and constraints. As we demonstrate, predictions based on channel sounding alone can be overly optimistic.

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