ALL THINGS 5G NR mmWAVE

AN UPDATE ON 5G NR MILLIMETER WAVE (mmWAVE) NETWORK PERFORMANCE AND NEW USE CASES

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Prepared by
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We wrote this whitepaper on behalf of Qualcomm. The test results presented in this paper are based on a combination of testing that we had done previously for our subscription-based *Signals Ahead* publication as well as testing that we did as part of this study.

In addition to providing consulting services on wireless-related topics, including performance benchmark studies, Signals Research Group is the publisher of the *Signals Ahead* and *Signals Flash!* research reports (www.signalsresearch.com).

Key Highlights

There have been several technology advancements which have made 5G NR easier to deploy, capable of achieving even higher data speeds, and introduced compelling new use cases.

A lot has happened with 5G NR (New Radio) in the last year since we published our first paper for Qualcomm on 5G NR. In addition to the proliferation of new 5G NR smartphone models, including mid-tier 5G NR smartphones, there have been several technology advancements which have made 5G NR easier to deploy, capable of achieving even higher data speeds, and introduced compelling new use cases. As an update to last year's whitepaper, we highlight some of the advancements associated with 5G NR mmWave (millimeter wave), or 5G NR deployed in millimeter frequency bands, specifically 28 GHz and 39 GHz in North America.

The most effective means of increasing data speeds is to increase the bandwidth of the radio channel(s) serving the mobile device. In the last several months the wireless ecosystem has increased the amount of mmWave bandwidth providing downlink and uplink data transfers, literally doubling the channel bandwidth in both directions by introducing larger downlink and uplink carrier aggregation schemes. Specifically, network infrastructure, chipsets, and mobile devices in North America now support eight 100 MHz channels (8x100 MHz or 8CC) in the downlink direction and two 100 MHz channels (2x100 MHz or 2CC) in the uplink direction. Previously, the limitation was 4CC in the downlink direction (cell site to mobile device) and 1CC in the uplink (mobile device to cell site).

Operators can now offer 5G NR mmWave fixed wireless access services.

In addition to increases in user data speeds, there are new 5G NR mmWave use cases, thanks to technology advancements as well as to the overall market maturity. Operators have always been interested in using 5G NR mmWave to offer fixed wireless access (FWA) services, and with the recent introduction of high-power CPEs (consumer premise equipment) and slight modifications to the configuration of the mmWave radio channel, the prospect of mmWave FWA is compelling. In addition to extending the effective range of the mmWave signal to several kilometers versus a few blocks, the high-power CPE enables mmWave signals to provide meaningful data speeds with near- and even non-line-of-sight (NLOS) radio conditions.

5G NR mmWave services are no longer limited to outdoor deployment scenarios. When deployed indoors, mmWave cell sites provide surprisingly good coverage for enterprise use cases. In effect, the mmWave signals extend well beyond LOS conditions, providing coverage in front and behind the 5G NR mmWave radio, as well as around hallway corners and into individual office spaces, thanks to the reflective nature of the mmWave signals.

Key highlights from our benchmark testing, which we cover in this whitepaper, include the following:

- 5G NR mmWave smartphones which support 8x100 MHz channels achieved nearly twice the data speeds as a smartphone, which is limited to 4x100 MHz channels, in side-by-side testing. Data speeds well above 3 Gbps are readily obtained in a commercial network.
- In addition to achieving higher data speeds, the 8CC feature is ideal for typical use cases, such as streaming video. We benchmarked the performance of 4K video streaming, including up to four individual 4K video streams to a single smartphone. In addition to delivering higher video quality, there weren't any video delivery impairments with substantial video impairments while using LTE as the radio bearer.
- 5G NR smartphones with 2CC uplink capabilities achieved nearly twice the data speeds as smartphones which only supported a single 100 MHz uplink radio channel. Uplink data speeds well above 100 Mbps are readily achieved even though the 5G NR mmWave radio channel dedicates most of its bandwidth to the downlink direction.

- We tested 5G NR mmWave FWA services at distances up to 5.1 kilometers, reaching nearly 2 Gbps at 1.7 kilometers, or nearly nine city blocks. The high-power CPE also delivered Gigabit-per-second speeds with near- and NLOS radio conditions in a commercial network, even when the CPE was pointed well off-angle from the serving cell site. Uplink data speeds were frequently higher than 100 Mbps, or much higher than possible with most fixed broadband service plans.

- In our enterprise testing of 5G NR mmWave, we observed Gigabit-per-second data speeds in hallways, a stairwell, and a conference room with the door closed. In many of these test locations, we couldn't see the serving 5G NR mmWave radio, meaning NLOS conditions. We attribute the results to mmWave reflections and the resiliency of mmWave signals which is much better than generally perceived.

Despite the progress made in the last year, there are additional opportunities for improvement, including:

- Channel bandwidths wider than 100 MHz are forthcoming – up to 2 GHz is possible, especially when 5G NR supports frequencies above 60 GHz.

- Improvements in how the network simultaneously schedules downlink and uplink data traffic over 5G NR and LTE will result in higher data speeds and more effective use of 5G NR and LTE network resources.

- Uplink carrier aggregation schemes beyond 2x100 MHz (2CC) will result in even higher uplink data speeds.

- 5G NR carrier aggregation schemes pairing sub 6 GHz and mmWave bands will improve downlink/uplink data speeds and extend the effective coverage of other compelling 5G NR attributes across an operator's footprint.

- Pending commercial support in early 2021 for some of the mmWave coverage enhancement features that we tested when we observed coverage at 5.1 kilometers in Wisconsin will make the case for rural mmWave FWA services more compelling.

- The continued introduction and deployment of 5G NR mmWave small cells that specifically target in-building use cases, including enterprise deployments, will make it easier and more economical to deploy in-building coverage.

For this study we primarily used 5G NR devices that we purchased from various retailers. These devices include the LG V60 UW, the OnePlus 8 5G UW, the Samsung Galaxy Note 20 5G UW, and the Samsung Galaxy A71 5G UW. These devices all use the Snapdragon X55 modem-RF system and the QTM525 mmWave antenna module. We also leveraged the Lenovo Flex 5G ACPC (Always Connected Personal Computer), which is powered by the Qualcomm Snapdragon 8cx 5G Compute Platform. For our testing in Chicago, we also used two Samsung Galaxy S20 Ultra smartphones, which use the Snapdragon X55 modem-RF. When testing FWA in Wisconsin we used a Qualcomm CPE reference design while our FWA testing in Minneapolis used the Wistron NeWeb Corporation LRV5-100 Internet Gateway – both CPEs use the Snapdragon X55 modem-RF along with the Qualcomm QTM527 mmWave antenna module. Lastly, for the initial uplink testing that we did in Minneapolis we used the Samsung Galaxy Note 10 (Snapdragon X50 modem-RF) and for the AT&T 39 GHz testing we used a Samsung Galaxy S20 Plus (Snapdragon X55 modem-RF).

In the next several sections, we highlight results from our testing of 5G NR mmWave networks.

Index of Figures

Background

Signals Research Group (SRG) has been conducting independent benchmark studies of chipsets, smartphones, and networks since our founding in 2004. Since these studies are done for our subscription-based *Signals Ahead* research product, they are completely independent since we monetize the studies through our corporate subscribers which span all facets of the ecosystem on a global basis.

We started testing 5G and 5G-like solutions starting in January 2018 when we tested a Verizon Wireless 5GTF (millimeter wave) trial network in Houston, Texas. Since that initial study, we've conducted an additional fourteen 5G NR benchmark studies through the end of 2020. These studies, which we've published in *Signals Ahead,* have included both mmWave and sub 6 GHz 5G NR networks, not to mention new capabilities and use cases. Recent examples include the Standalone (SA) network architecture (August 2020), Dynamic Spectrum Sharing (DSS – December 2020), and mmWave Fixed Wireless Access (FWA – December 2020). As part of this study, we conducted additional 5G NR mmWave testing, including 8CC and 2CC uplink in Chicago (October 2020) and long-distance 5G NR mmWave FWA in rural Wisconsin (September 2020).

Thanks to our test and measurement partner companies, which we identify in the test methodology section, our studies involve deep analysis of multiple network parameters, so they provide meaningful insight into how networks really perform. If something works well, we can show it. Conversely, if there are performance issues or opportunities for improvement, we can generally find them and identify the likely cause(s) of the problem.

Qualcomm reached out to us mid-summer and asked us to update an earlier 5G NR study that we did on behalf of Qualcomm in 2019, this time with a particular focus on mmWave, including recent technology advancements and features, as well as new use cases. This paper includes results and analysis from a mix of tests that we did on our own behalf for *Signals Ahead* as well as tests that we did specifically for this study. Throughout this paper we identify studies that we did for *Signals Ahead* and those studies that we did for this paper.

Higher carrier aggregation schemes, up to 8x100 MHz channels, and PDCP data combining with LTE have more than doubled data speeds since 5G NR was first introduced

Although it isn't noticeable to the casual observer, 5G NR smartphones almost always use multiple mmWave radio channels, as well as at least one LTE radio channel, when receiving data (a.k.a. the downlink direction). The use of multiple 5G NR radio channels is called carrier aggregation and it is based on the same underlying principles that originated with 3G (DC-HSDPA) and 4G LTE-Advanced networks. LTE networks and devices can only support a maximum channel bandwidth of 20 MHz (5 MHz with 3G) so to leverage more spectrum and deliver the subsequent higher data speeds, the industry adopted carrier aggregation to logically combine multiple radio channels with an aggregate bandwidth greater than inherently supported by the respective standard.

In the future, a single 5G NR radio channel could be up to 2 GHz wide, or 20x what is possible today.

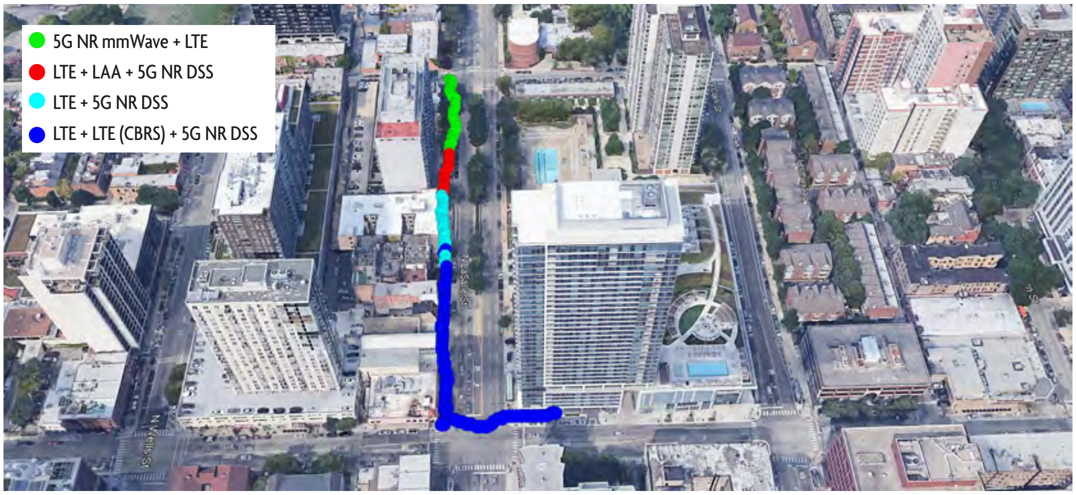
With 5G NR mmWave, the maximum channel bandwidth is presently 100 MHz, although this value will increase with future capabilities, including when 5G NR operates in frequencies greater than 60 GHz. A single radio channel could be up to 2 GHz wide, or 20x what is possible today. If an operator today has more than 100 MHz of mmWave spectrum they need to use carrier aggregation to allocate all the mmWave spectrum to a mobile device, thereby achieving the maximum possible data speeds. When operators first launched commercial 5G NR mmWave services in 2019, the industry only supported up to four 100 MHz channels, even though some operators had more than 400 MHz of mmWave spectrum. In effect, operators couldn't use all their spectrum or at least they couldn't allocate all their mmWave spectrum to a single mobile device.

When we did our first 5G NR mmWave benchmark study shortly after the networks launched, we observed sustained physical layer downlink data speeds of 1.2 to 1.3 Gbps with peak downlink data speeds in the range of 1.5 to 1.6 Gbps. In addition to the 4x100 MHz limitation, we also observed some inefficiencies in how 5G NR leveraged the three additional 100 MHz channels – generally referred to as secondary carriers throughout the industry and in this whitepaper. Later in 2019 the inefficiencies diminished, and we were able to observe sustained downlink data speeds approaching 2 Gbps in a commercial 5G NR mmWave network.

In October 2020, SRG conducted a 5G NR mmWave benchmark study in Chicago, IL using several commercially procured smartphones as well as two Samsung Galaxy S20 Ultra smartphones with firmware that supported 8x100 MHz radio carriers, or twice the total channel bandwidth of the other 5G NR smartphones that we had in our possession. The next several figures highlight some of the findings from this study, which we did to support this paper.

Figure 1 shows a portion of a walk test that we did along North LaSalle Street, turning onto East Division Street. The colored circles illustrate the technologies/frequency bands the smartphone was using during the walk. At the beginning of the walk, the smartphone was using mmWave spectrum (8x100 MHz) along with an LTE carrier for the anchor band. Once we walked outside of the mmWave coverage area, the smartphone switched to a mix of LTE, LAA (LTE in unlicensed spectrum) and 5G NR DSS (Dynamic Spectrum Sharing), using the operator's 850 MHz spectrum. Finally, the blue circles signify where the smartphone used LTE, including LTE in CBRS spectrum, and 5G NR DSS, once again in the operator's 850 MHz band.

Figure 1. Pedestrian Route – Downtown Chicago



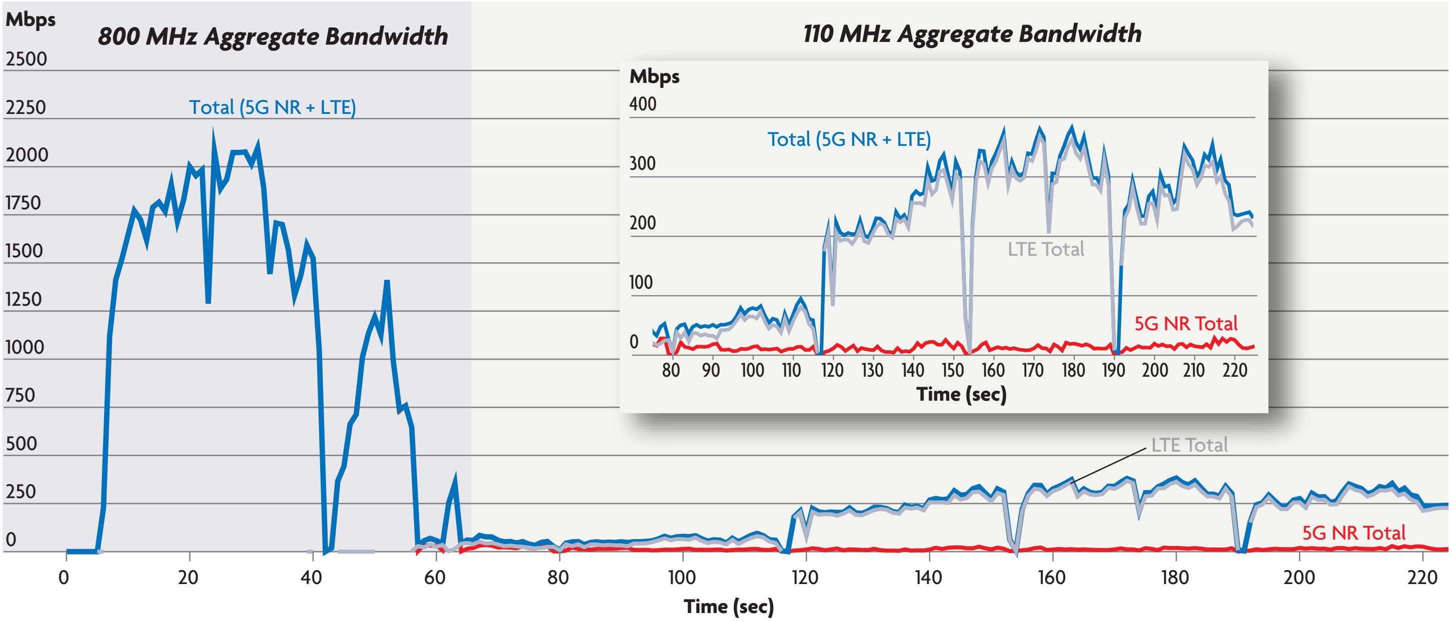
Source: Signals Research Group

mmWave doesn't need to achieve ubiquitous coverage before providing benefits to an operator and to consumers.

This figure depicts a rich mix of technologies/frequencies that the smartphone used, and it reflects how operators are using mmWave spectrum alongside their other network resources. While mmWave coverage will continually improve with the deployment of additional cell sites, from a mobility perspective it doesn't need to achieve ubiquitous coverage before providing benefits to an operator and to consumers. In high traffic areas, mmWave will deliver the necessary capacity and offload traffic from the operator's LTE and 5G NR low- and mid-band deployments. Outside of mmWave coverage, the smartphone will continue leveraging 5G NR, albeit with DSS functionality in which LTE and 5G NR data traffic share a common radio channel. Further, there is LAA today (5G NR-U tomorrow) and CBRS today (C-Band tomorrow) to provide meaningful data speeds and capacity via 5G NR.

In Figure 2 we've plotted the downlink physical layer throughput, including individual contributions from 5G NR and LTE. When we tested this network, there wasn't any LTE data throughput when there was 5G NR mmWave throughput but when there was 5G NR DSS throughput there was LTE throughput, hence the total throughput with mmWave was comprised entirely of 5G NR throughput. The figure also includes an inset with a different Y axis scale to provide additional visibility into the throughput during the last two minutes of the test. The disparity in the throughput largely reflects the vast differences in the total channel bandwidth – 800 MHz versus ~110 MHz – used to achieve the data speeds, but it also illustrates why operators are leveraging 5G NR mmWave in their network deployments.

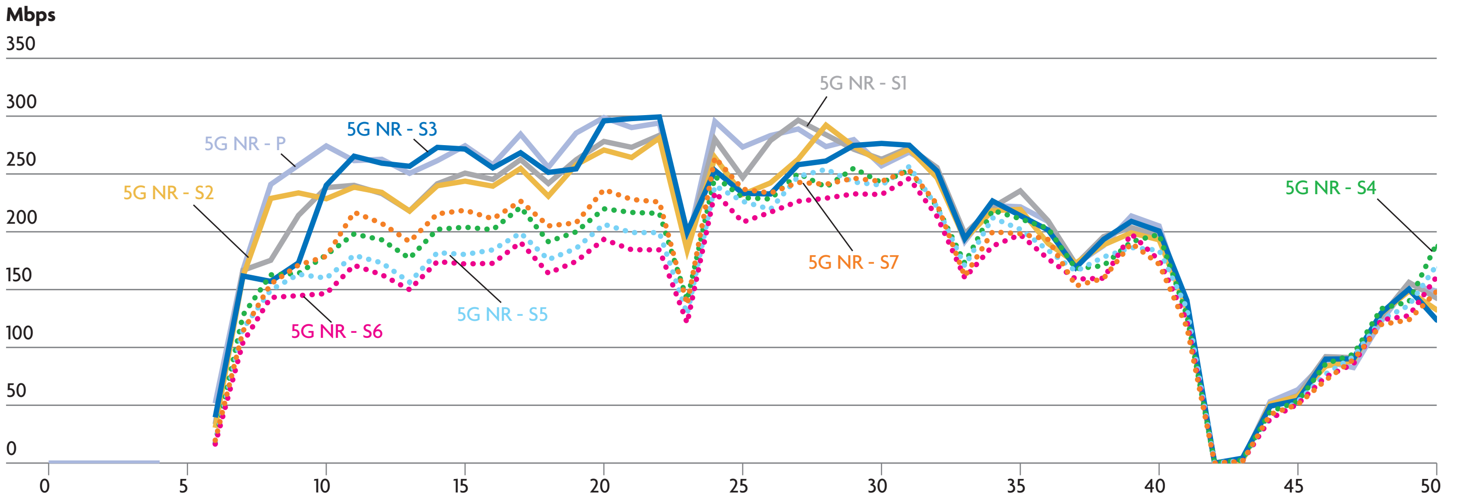
Figure 2. Downlink Throughput



Source: Signals Research Group

As just indicated, this 5G NR cell site (gNB) supported 8x100 MHz radio carriers with each radio carrier contributing to the total throughput shown in Figure 2. Figure 3 provides additional granularity into the 5G NR mmWave performance by showing the contributions of each 5G NR radio channel to the total throughput. The figure is arguably a bit busy, but this situation is entirely due to the use of eight radio carriers and the benefits that each radio carrier brings to the total throughput.

Figure 3. 5G NR mmWave Downlink Throughput – by component carrier

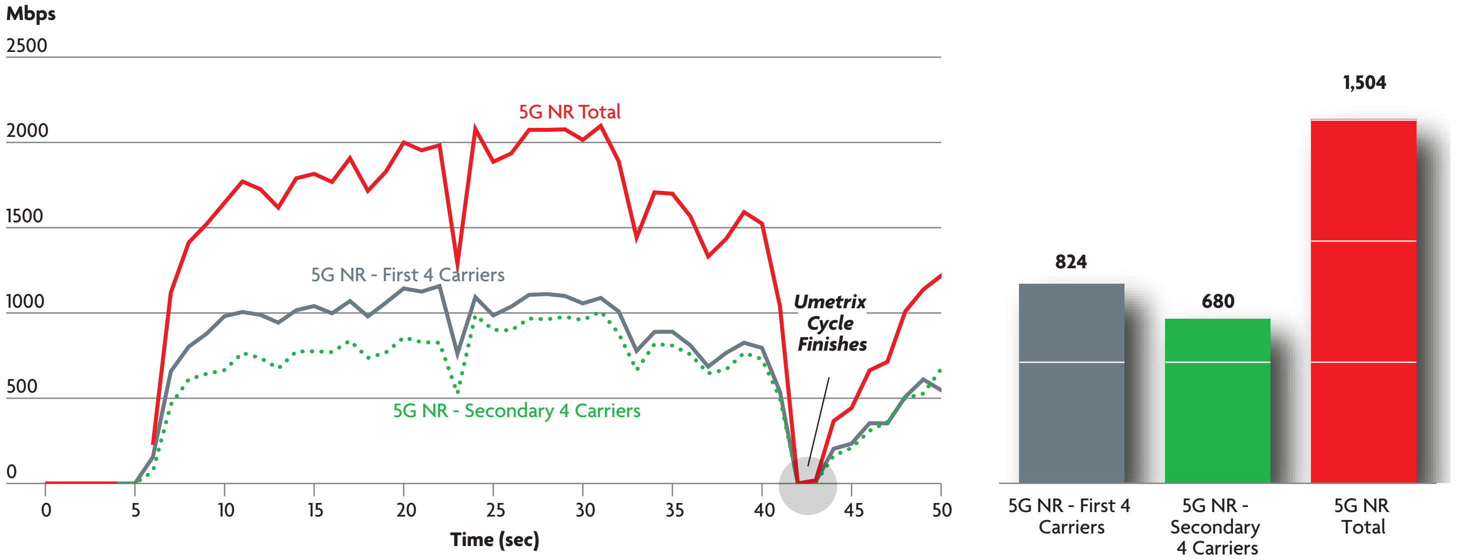


Source: Signals Research Group

The average throughput increased by 85% due to the introduction of the additional 4x100 MHz of spectrum.

Figure 4 simplifies the results by aggregating the eight unique carriers into groups of four carriers – labeled “First 4 Carriers” and “Secondary 4 Carriers” in the figure. The best way to interpret the information in the figure is to equate the throughput from the first 4 carriers with what is possible with a network and smartphone that only supports 400 MHz of spectrum and the summation of the two throughputs – labeled “5G NR Total” – to what is possible with a network and smartphone that

Figure 4. 5G NR mmWave Downlink Throughput – first four carriers and second four carriers

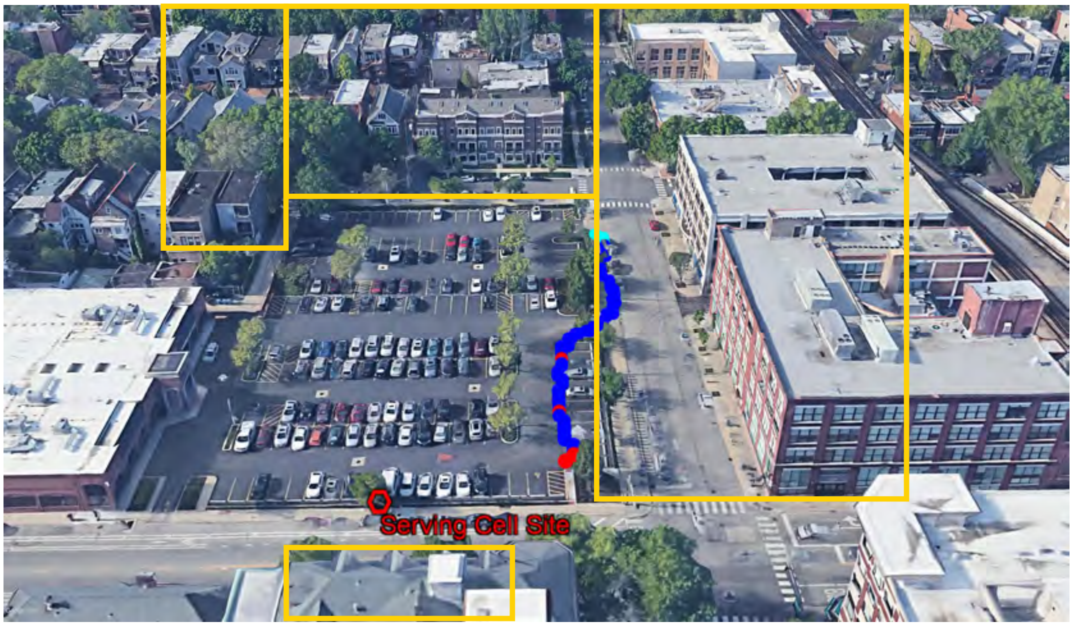


Source: Signals Research Group

support 800 MHz (8x100 MHz) of spectrum. To summarize, the average throughput increased by 85% due to the introduction of the additional 4x100 MHz of spectrum. Figure 4 also highlights a few seconds between 40-45 seconds when the data transfer finished its cycle before starting a new test. These occurrences, which result from the test scenario we were using and not from network performance, are also evident in Figure 2.

We did additional testing of 8CC (8 component carriers) further north of downtown Chicago in Lincoln Park. We point out that for this study we limited the testing to a few cell sites which supported 8CC since the primary objective was to compare 8CC and 4CC smartphones at a 5G NR cell site that supported 8CC. Figure 5 shows the area where we tested near DePaul University, including the location of the gNB and the route that we walked with one of the smartphones (the full test scenario is explained in a subsequent paragraph). In the figure, we've also inserted four yellow rectangles. These rectangles show buildings (dorms, offices, and multi-tenant complexes) where the same mmWave cell site should be able to provide fixed wireless access services with a high-power CPE. We examine the FWA use case in a subsequent section of this paper.

Figure 5. Lincoln Park Test Location

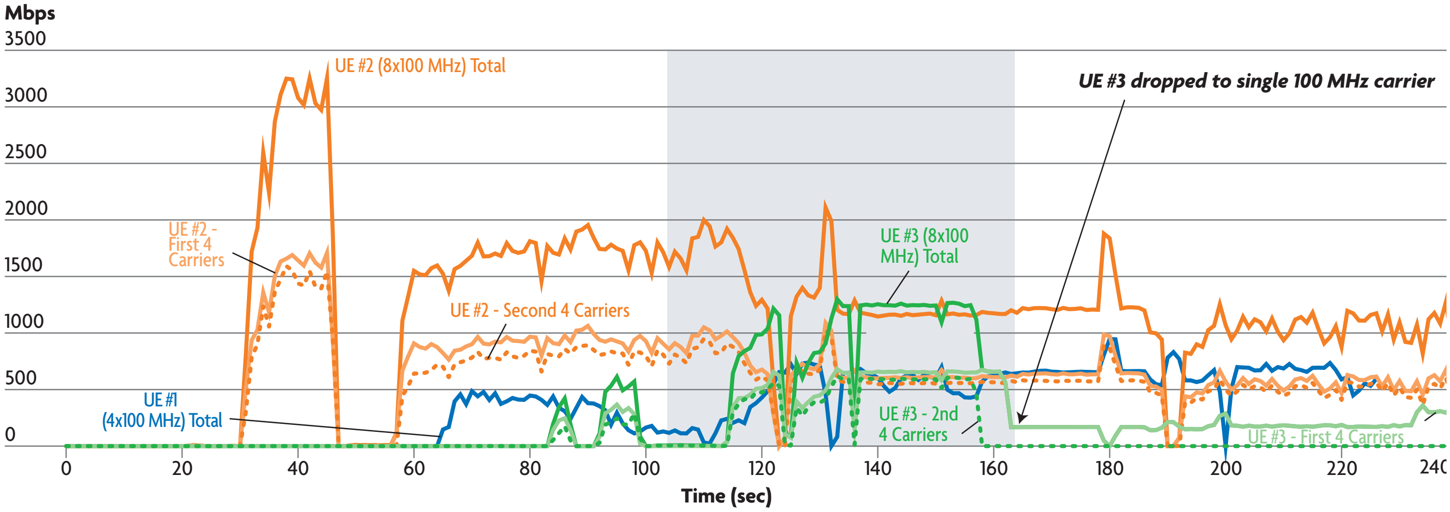


Source: Signals Research Group

For this first test, we used three smartphones. Two smartphones (labeled UEs or User Equipment) supported 8x100 MHz of 5G NR mmWave and the third smartphone (UE #1) only supported 4x100 MHz. In this test, UE #1 was mobile and the other two smartphones remained stationary throughout the test. The different colored circles in Figure 5 illustrate the different SSB (Synchronization Signal Block) beam indices the smartphone used as we walked through the test area. The SSB contains synchronization information that helps the mobile device attach to the serving cell site. With beamforming, which is a critical feature of mmWave since it helps overcome the coverage limitations of mmWave, the SSB values are unique to each beam so these types of plots help illustrate how beamforming is used in the network.

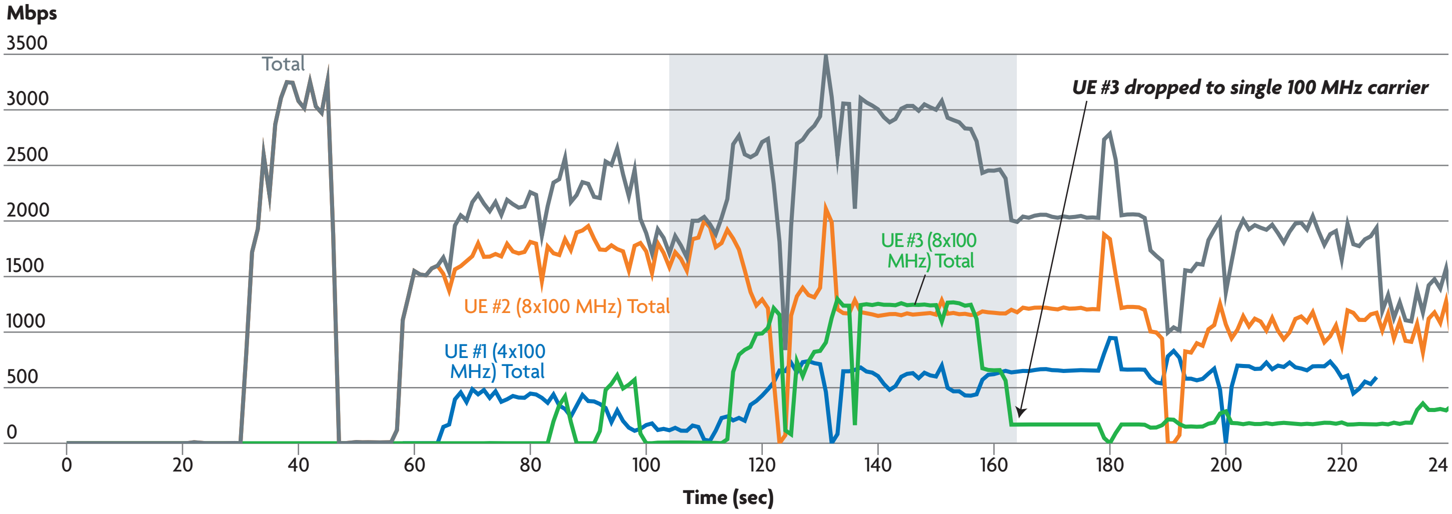
Figure 6 shows a time series plot of the throughput for each smartphone (UE) as well as the contributions from the first four and the second 4 carriers for the two smartphones that supported 8CC. Figure 7 shows results from the same test, but in this case the figure only shows the total throughput for each smartphone as well as the summed throughput for all three smartphones, labeled "Total" in the figure. At the start of the test, we only attached to the network with UE #2 and due to 8CC its peak data speed exceeded 3.2 Gbps – the first four and second four carriers contributed roughly equal amounts to the total throughput. Another point worth making is that the total throughput with all three smartphones attached frequently exceeded 2 Gbps with a peak of 3.5 Gbps. It is also evident that UE #1, which only supported 4CC meaningfully underperformed the other two smartphones, which supported 8CC. Lastly, in Figure 6 we've highlighted the point when UE #3 stopped using 8CC and reverted to using a single 100 MHz radio carrier. It isn't clear why this happened, but it is evident that the absence of the seven additional carriers had a meaningful impact on the smartphone's total throughput.

Figure 6. Lincoln Park Test Results – by UE with details



Source: Signals Research Group

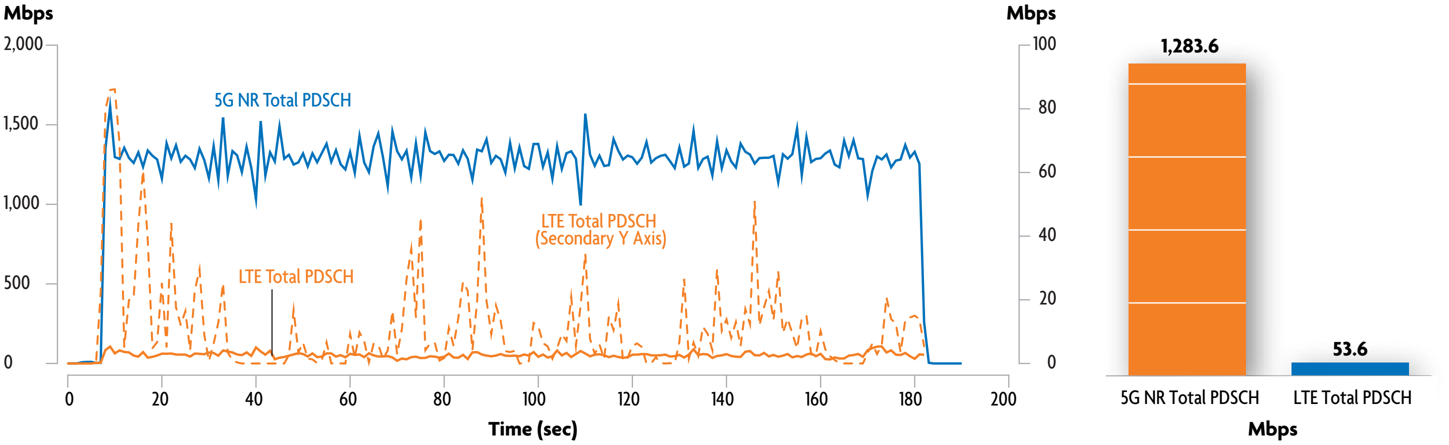
Figure 7. Lincoln Park Test Results – by UE with total throughput



Source: Signals Research Group

In addition to the recent introduction of 8CC, 5G mmWave also supports concurrent data transfers with LTE, using a feature called PDCP (Packet Data Convergence Protocol) split bearer combining. When mmWave networks first launched, the smartphone received all its data over 5G NR, or it received all its data over LTE – generally during handovers or when moving outside of 5G NR mmWave coverage. With PDCP split bearer combining, the network sends data simultaneously over both radio bearers, effectively increasing the amount of total channel bandwidth and the associated data speeds. Figure 8, which we previously published in a Signals Ahead report, shows results from testing in AT&T's 39 GHz (Band n260) network in Dallas, Texas last summer. The time series plot shows the individual contributions from 5G NR and LTE during the three-minute test. For additional clarity, the figure also shows the LTE throughput along the secondary Y axis (dashed line). The contribution from LTE (53.6 Mbps) seems modest relative to the average 5G NR data speed (1,283.6 Mbps), but from a different perspective the LTE data speed is representative of a typical user experience on today's LTE networks. In other words, with PDCP combining the user gets the benefits of LTE plus the substantial benefits of 5G NR mmWave.

Figure 8. 5G NR and LTE PDCP Split Bearer Combining



Source: Signals Research Group

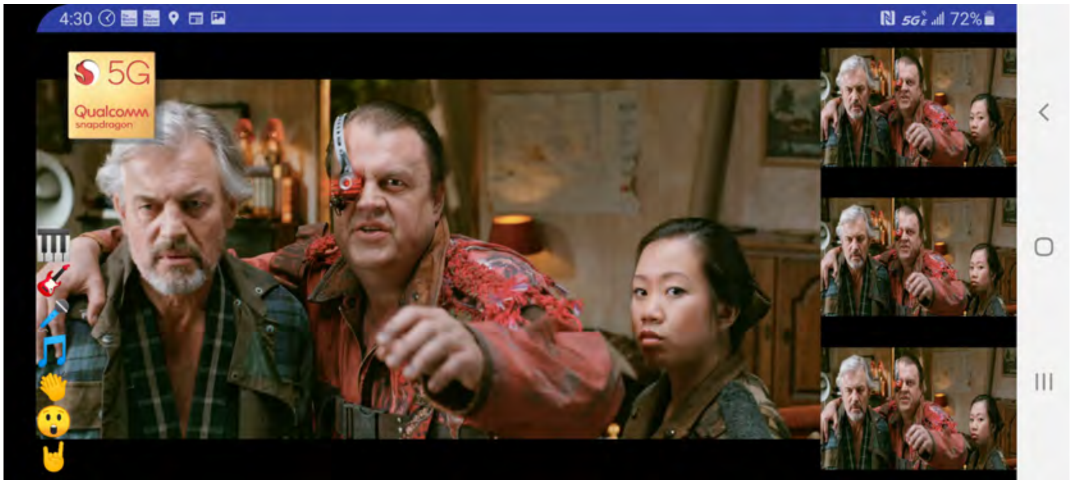
We anticipate PDCP split bearer functionality to improve in the future with better utilization of the two radio bearers and with more LTE carriers included in the mix. In this test, there were multiple LTE radio carriers present, but the smartphone only used a single radio bearer (LTE Band 2) in this test. Transmitting data packets over two radio bearers from within the operator's core network is a complex process since there are significant differences in the maximum data speeds between the two networks. As the algorithms which route traffic over the two radio bearers improve, the schedulers in the 5G NR and LTE radios will have more packets available to transmit, meaning increased efficiency of the radio bearers, increased usage of LTE carrier aggregation, and even higher data speeds to consumers.

5G NR mmWave delivers the capacity necessary to sustain multiple 4K video streams to a single smartphone and deliver a great user experience

As part of our 8CC testing in Chicago, we evaluated the user experience of 5G NR mmWave with use cases that went beyond simply measuring the peak and average data speeds that 8CC can deliver. In this section, we present some results from testing 4K video streaming, involving both 5G NR mmWave (8CC) and LTE, as well as streaming multiple 4K videos to a single smartphone.

We used two different mechanisms to stream video to our smartphones. First, we used a multi-screen video application developed by Qualcomm to simultaneously stream four 4K videos to a single smartphone. For simplicity, we used the same 4K video, streamed from four different URLs, for all video streams (reference Figure 9), although a typical use case would involve four unique video streams. For example, attendees at a concert or sports event could watch four different views of the stage or field, even follow multiple golfers on the front and back nine.

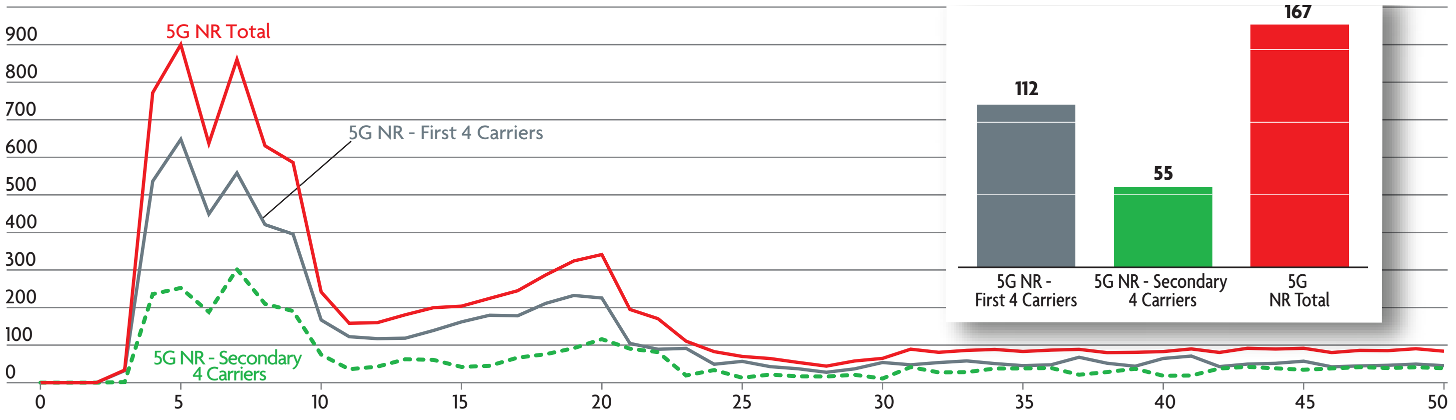
Figure 9. Multi-Screen Content to a Single Smartphone



Source: Signals Research Group

Figure 10 shows the total throughput for the four 4K videos as well as the individual contributions from the first four carriers and the second four carriers. The inset bar chart shows the average bandwidth for the first fifty seconds of the test. Including some video pre-caching at the beginning of the video streams, the average throughput was 167 Mbps with 55 Mbps (33%) associated with the second four carriers.

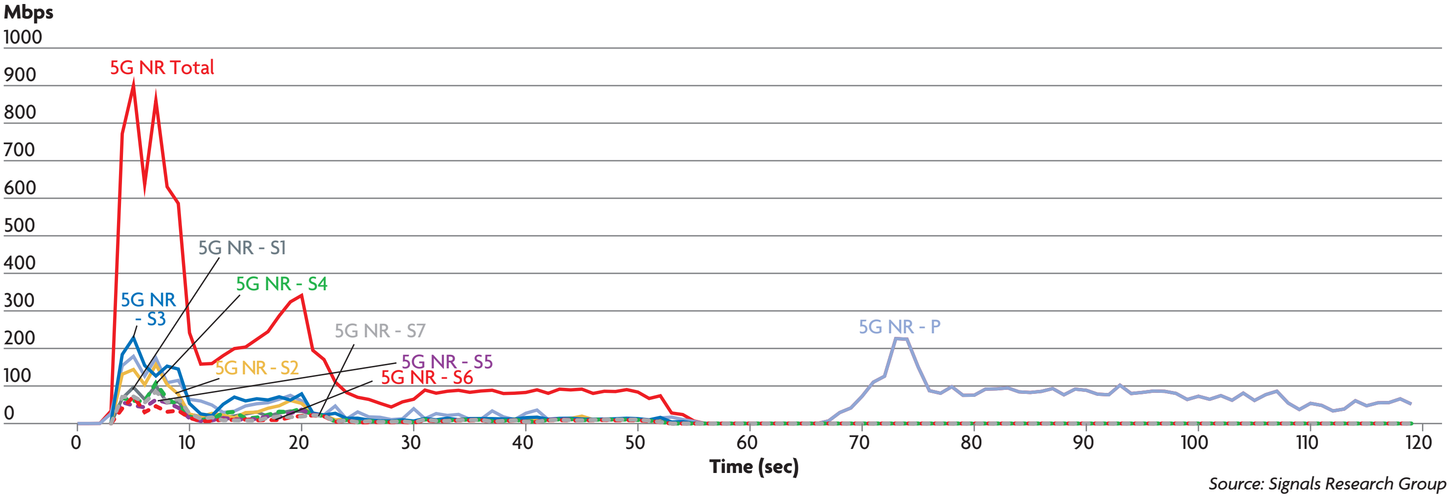
Figure 10. 5G NR mmWave Throughput with Four 4K Video Streams – by first four and second four carriers



Source: Signals Research Group

Figure 11 shows the individual contributions from all eight 5G NR mmWave carriers for the first 120 seconds of the test. Looking at the last 40 seconds of the test, it is evident the four 4K videos required a sustained throughput close to 100 Mbps, which is consistent with our expectations, and that a single 100 MHz channel could deliver the necessary throughput. While true, it is critical to note that we did this test in an "empty network" and that this use case inherently implies many simultaneous video streams to attendees at the venue. Sustaining multiple 100 Mbps unicast video streams is only possible with large amounts of bandwidth – bandwidth that is only available in millimeter wave spectrum.

Figure 11. 5G NR mmWave Throughput with Four 4K Video Streams – by component carrier



Source: Signals Research Group

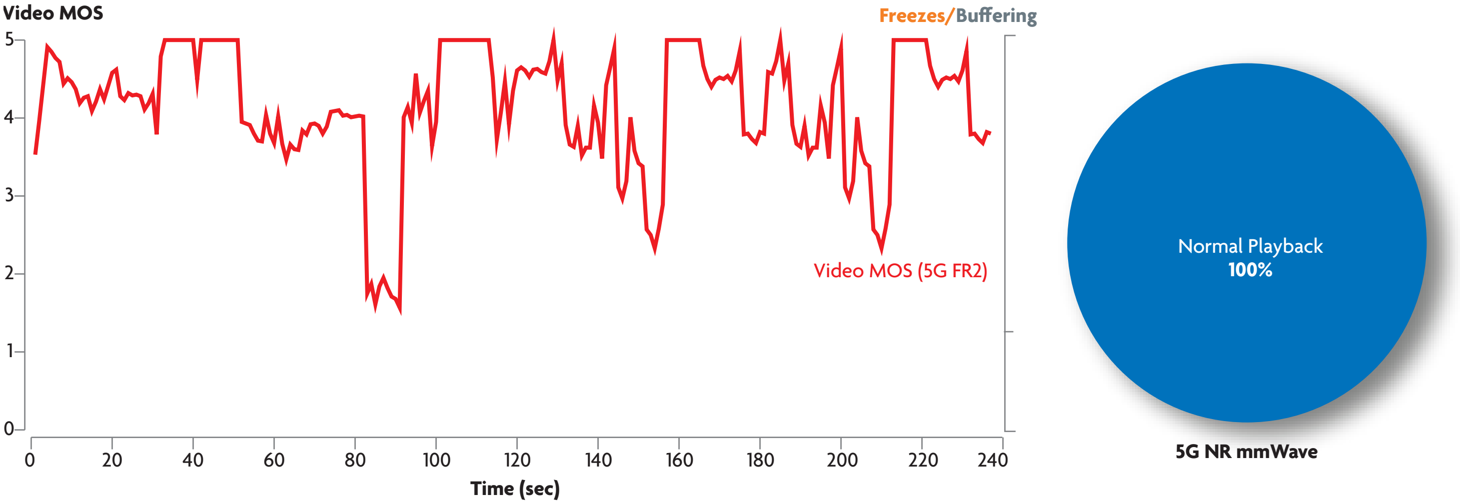
We also streamed a 4K video from YouTube to evaluate the video performance (video quality and video delivery) as well as the bandwidth required to sustain the video playback. Figure 12 shows a screen capture of the 4K "Safari" video that we used for this test.

Figure 12. 4K Safari Video – streamed over 5G NR mmWave

Source: Signals Research Group

Figure 13 provides a time series plot of the video KPIs, including the video mean opinion score (MOS), the amount of freezing, and the amount of buffering that occurred during the test. As shown in the time series plot and the adjacent pie chart, there wasn't any buffering or freezing when viewing the video. The video MOS is based on several underlying metrics to determine the quality of the images. Although there are a few dips in the MOS, the overall quality of the video was quite strong, especially relative to the LTE results, which we show in a bit. We repeated this test a few times and we never noticed any discernable differences in the video quality when these dips occurred. Furthermore, these dips occurred in the same spots during the streaming of the video, suggesting to us there was something about the imagery in the video, and not the actual video quality, which was causing the drops to occur.

Figure 13. 4K Safari Video KPIs – streamed over 5G NR mmWave



Source: Signals Research Group

After testing over 5G NR mmWave we repeated the same test with LTE, in this case the LTE data connection involved two LTE carriers (i.e., carrier aggregation). We picked a random spot outside of 5G NR mmWave coverage for this test, using the same smartphone that we used for the earlier video test. Figure 14 shows a screen capture of the video being streamed over LTE – note the spinning circle in the middle of the image, indicating buffering.

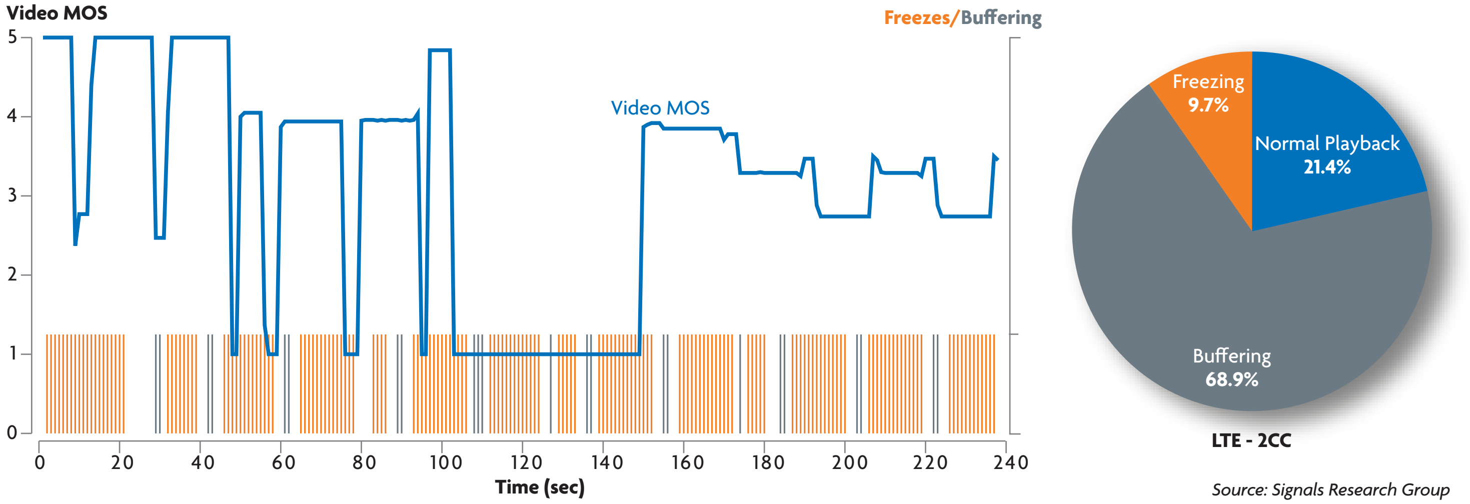
Figure 14. 4K Safari Video – streamed over LTE with 2CC

Source: Signals Research Group

The 4K video was frozen or buffering for 78.6% of the time when streaming over LTE.

Figure 15 shows a time series plot of the video KPIs as well as a pie chart which aggregates the amount of time the video played normally versus buffering or freezing. As shown in the two images, the video froze or buffered for 78.6% of the time. Furthermore, there was a meaningful drop in the video quality (MOS) when streamed over LTE. We point out that video MOS does not consider freezing or buffering since the algorithm only analyzes the quality of the video, not if it is a still image or a seamless streaming video. These results do not necessarily reflect the typical performance over an LTE network, although they are accurate for the randomly selected location where we performed this test. However, the point remains that LTE networks are becoming congested and that there simply isn't always enough bandwidth available to support lots of 4K video traffic, let alone a single 4K video stream that we tried to do in this test.

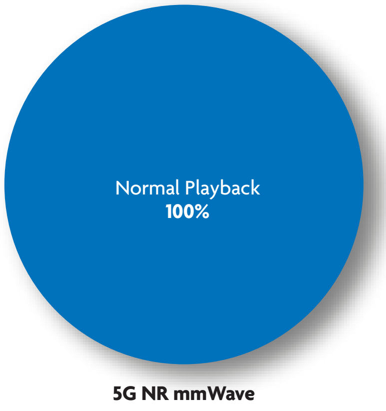
Figure 15. 4K Safari Video KPIs – streamed over LTE with 2CC



Source: Signals Research Group

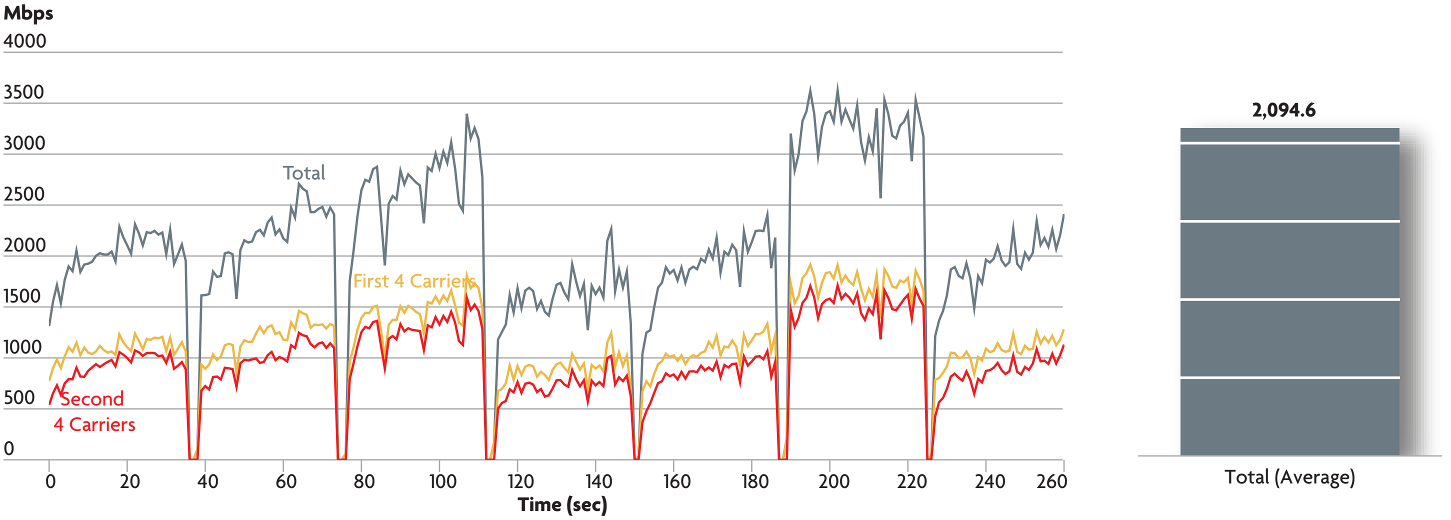
To conclude this section on 4K video streaming over 5G NR mmWave, we include one last test in which we streamed the same 4K safari video over 5G NR mmWave using a smartphone that supported 8CC. At the same time, we had another 5G NR mmWave smartphone (8CC) sitting next to the first smartphone, downloading large amounts of data. As shown in Figure 16, the video performed flawlessly without any buffering or freezing taking place. Equally impressive, this result was achieved while the other smartphone was downloading data at an average speed of ~2.1 Gbps, as shown in Figure 17.

Figure 16. 4K Video Impairments with Concurrent 5G NR Download



Source: Signals Research Group

Figure 17. Simultaneous Data Transfer Results to an 8CC-capable 5G NR Smartphone



Source: Signals Research Group

5G NR mmWave with a high-power consumer premise equipment (CPE) significantly enhances the fixed wireless access (FWA) market opportunity.

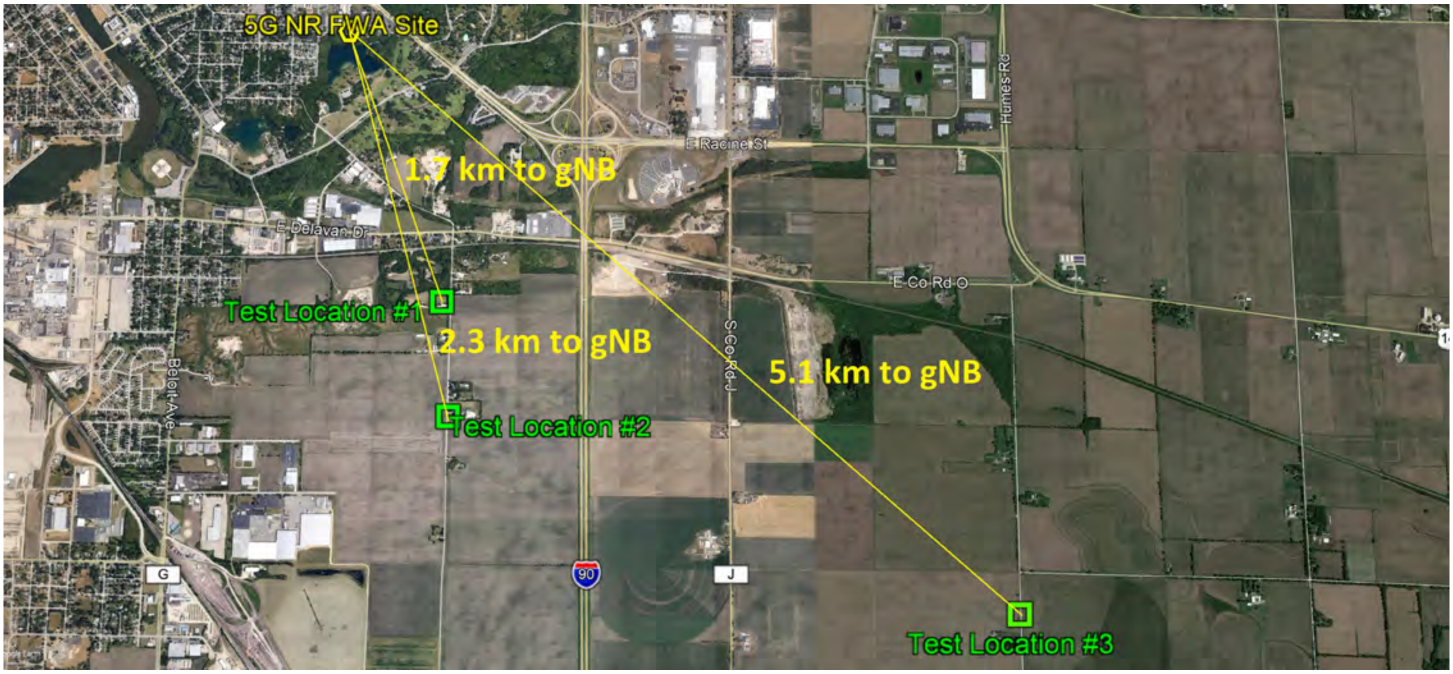
As part of this study, we conducted some field tests of 5G NR mmWave in rural Wisconsin, using the US Cellular network, Ericsson infrastructure, and a Qualcomm high-power extended range mmWave CPE reference design with the QTM527 antenna module. US Cellular had mounted the 5G NR radio on a traditional cell tower so its height above the ground was considerably higher than the height when the 5G NR radio is located on a lamp pole. The 5G NR mmWave radio also supported traditional enhanced mobile broadband (eMBB) services, meaning anyone with a mmWave smartphone could attach to the 5G NR radio – something we did during our testing. However, by mounting the 5G NR radio further from ground level it improved the view of the surrounding countryside, and, in theory, increased the coverage area. We were there to independently confirm the latter statement.

Figure 18. 5G NR mmWave FWA Cell Site

Source: Signals Research Group

We tested at three different locations – 1.7 km, 2.3 km, and 5.1 km (> 3 miles) – moving further away from the cell site with each test. At each location we used a lift to raise the CPE above ground level and to simulate a typical elevation in which the CPE is mounted on the roof of a house in the area. To put things in perspective, at the closest distance we were approximately 8.5 city blocks away from the cell site or significantly further than anything we've observed in all our previous 5G NR mmWave tests with a smartphone in an urban environment. Figure 19 illustrates the location of each test site relative to the serving cell site.

Figure 19. Rural Wisconsin 5G NR FWA Test Locations



Source: Signals Research Group

At each test site we took a picture of the distant cell tower, which was only visible to the naked eye at the closest location to the cell tower. At the other two locations, we merely pointed our camera in the direction of the cell tower and took a picture. Figure 20 shows these three images. Since we didn't use the zoom feature on our smartphone and we didn't publish these images in full resolution in this paper, the tower isn't clearly visible at 1.7 km.

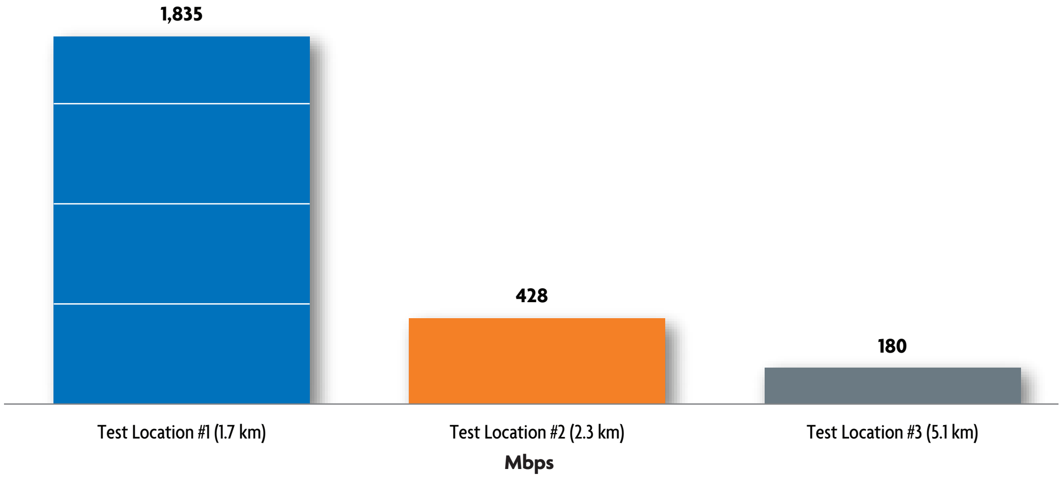
Figure 20. Three Views of the 5G NR Cell Site

5.1 km to gNB *2.3 km to gNB* *1.7 km to gNB*

Source: Signals Research Group

Figure 21 provides the average 5G NR physical layer data speeds from these three tests

Figure 21. FWA Test Results



Source: Signals Research Group

The high-power CPE and enhancements to the infrastructure were essential to achieving these results.

We attribute the results at these distances to two factors. First, the CPE with the Qualcomm QTM527 antenna module had much better receive sensitivity and transmit power than a traditional smartphone where the performance is constrained by size and power limitations. Secondly, the infrastructure, especially some of the data and control channels, required some enhancements to support the greater distances since the typical protocol configurations didn't anticipate these distances so the settings weren't optimized for the length of time required to for the gNB and CPE to communicate with each other.

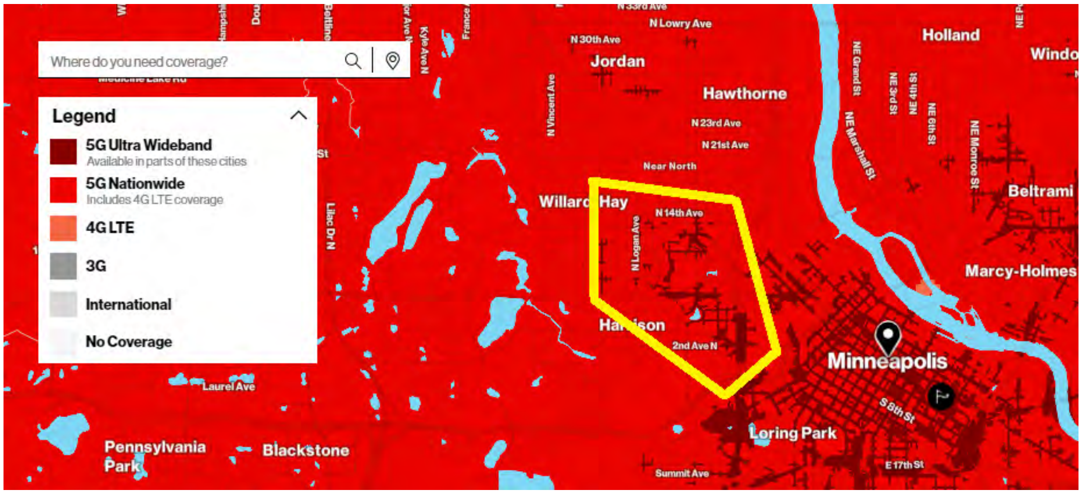
Although it is unlikely operators will offer 5G NR mmWave FWA services to households residing 5.1 km from a cell site, these results indicate the effective range of mmWave is easily a few kilometers with line-of-site (LOS) conditions. Conversely, operators can leverage the performance attributes of a high-power CPE to offer FWA services to households that live relatively close to the serving cell site (i.e., 1 km), but with more challenging radio conditions, including near-LOS and even non-LOS transmission paths.

Although it wasn't part of this study, SRG did an analysis of the Verizon Wireless 5G Home Internet Service, which we published in a December 2020 Signals Ahead report. 5G Home Internet Service is a branded service offering that provides fixed wireless access broadband services using the operator's 5G NR mmWave network (28 GHz, Band n261). For this study, we used a commercially available Wistron NeWeb Corporation LRV5-100 Internet Gateway with the Qualcomm QTM527 antenna module to test at random locations in Minneapolis and Saint Paul, Minnesota. Since SRG HQ is located just west of Minneapolis, we have reasonably good familiarity with the area although when we did the tests, we had no idea where the 5G NR cell sites were located. We were able to determine the locations of the cell sites and their corresponding PCI (Physical Cell Identity) after finishing the testing.

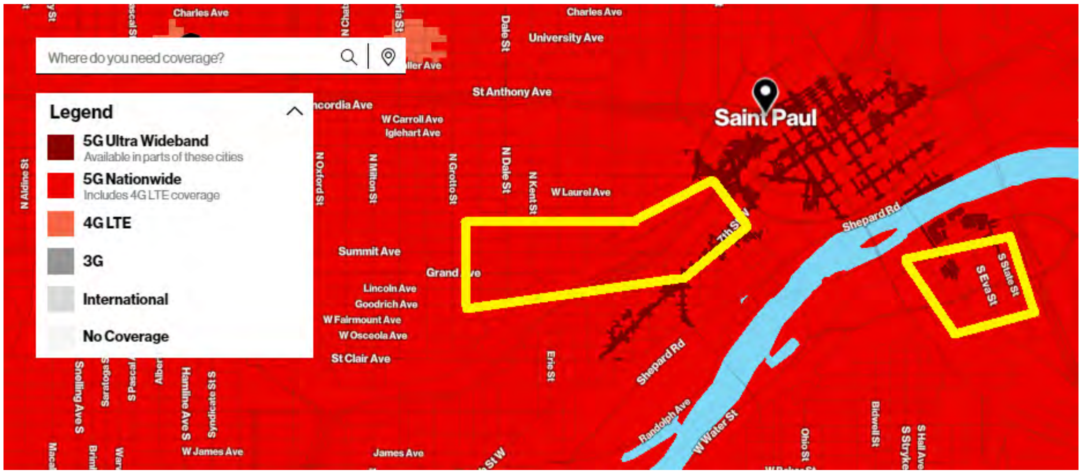
We observed Gigabit-per-second data speeds with near-LOS and non-LOS conditions with distances that were frequently in the range of 500 to 800 meters from the serving cell site.

Figure 22 shows the areas where we tested in the two cities. We picked these three areas because we knew there was at least some mmWave coverage in the area, plus these neighborhoods were outside of the urban corridor so we thought the test scenarios might be more interesting. In hindsight, these test areas were far more interesting than we could have imagined. For example, it was very evident to us that the 5G NR mmWave cell sites in the Minneapolis test area were primarily targeting FWA services since the residential area wouldn't generate enough mobile data traffic to require mmWave coverage – unless the mmWave coverage was also serving the numerous single-family and multi-tenant residences in the area with FWA services. More importantly, we observed how the high-power CPE could leverage its performance attributes to achieve Gigabit-per-second data speeds with near-LOS and non-LOS conditions with distances that were frequently in the range of 500 to 800 meters from the serving cell site.

Figure 22. Minneapolis and Saint Paul 5G NR mmWave FWA Test Areas



Minneapolis Test Area



Saint Paul Test Area

Source: Signals Research Group

We tested at more than fifty locations in these three neighborhoods. Typical average downlink speeds were between 1 Gbps and 1.5 Gbps, including at locations where we later discovered the CPE was facing well off-angle from the direction of the serving cell site or there were significant obstacles, such as buildings and lots of trees, obscuring the view of the cell site. Uplink speeds, which included at least some contributions from LTE (PDCP split bearer combining), almost always exceeded 100 Mbps, or well beyond what most fixed line broadband services deliver. In markets with 800 MHz of spectrum – Verizon has 400 MHz of spectrum in these two cities – and with the future support of 2CC uplink capabilities, these data speeds will improve. We also observed the mmWave coverage in these neighborhoods was substantially better than implied by the coverage maps shown in Figure 22. Anecdotally, we've encountered very large clusters of mmWave cell sites in other cities outside of Minnesota. Like we observed in Minneapolis, these mmWave clusters were in suburban neighborhoods where there isn't high mobile data traffic, suggesting to us that the operator is much further along with its mmWave FWA deployments than we expected.

The high-power CPE had a 25 dB performance advantage over the smartphone.

Out of extreme curiosity, we compared the high-power CPE performance with a typical 5G NR mmWave smartphone. At most locations where we did our tests, the smartphone couldn't attach to the serving 5G NR cell site, but in those locations where it was successful, we found the high-power CPE had a 25 dB performance advantage over the smartphone – 3 dB equates to a doubling in the signal strength so clearly the benefits of the high-power CPE were compelling. We recognize this comparison isn't entirely fair since mmWave deployments for smartphone usage target high data traffic areas where there isn't any need to cover great distances from a single cell site. However, we include the comparison to emphasize that mmWave FWA is a completely different use case from mmWave eMBB, and that most consumers or industry followers can't easily extrapolate their experiences with mmWave eMBB to mmWave FWA. In non-technical terms, you must see it to believe it.

mmWave isn't the only spectrum suitable for FWA as operators are using, or planning to use, mid-band spectrum for FWA. In fact, in some more rural areas operators are already offering FWA services with low-band LTE or 5G NR. Our belief is that both mmWave and mid-band spectrum (2.5 GHz to 5 GHz) will play a role in offering FWA services. Much depends on the population density of the targeted coverage area and the service plans the operator wants to promote. mmWave will never have the coverage profile of mid-band spectrum so mid-band spectrum is generally better positioned for lower population density areas.

There isn't sufficient mid-band spectrum to deliver the data speeds and capacity that are possible with mmWave.

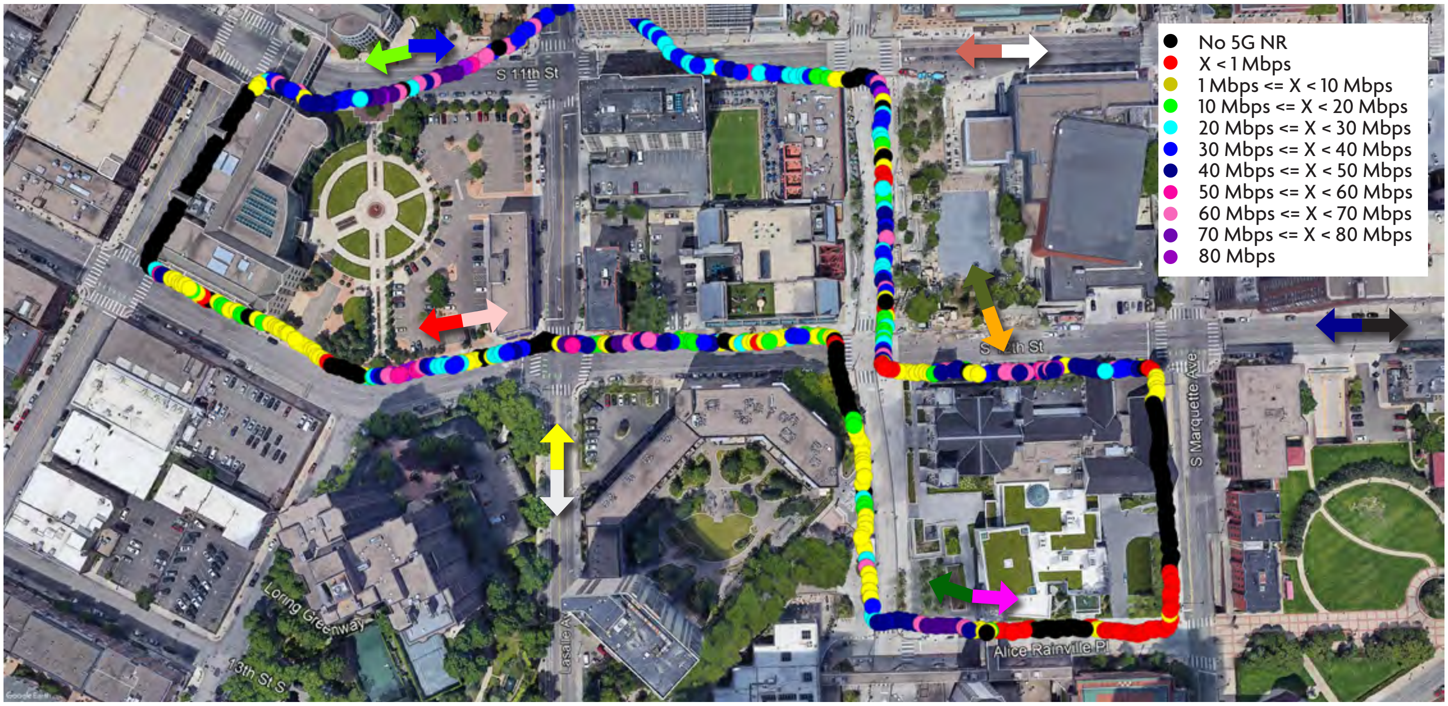
Conversely, there isn't sufficient mid-band spectrum to deliver the data speeds that are possible with mmWave, plus mmWave spectrum is ideal for offering unlimited data usage since there is more inherent capacity available. The high-power CPE and modifications in the infrastructure to increase the coverage profile of mmWave help close the gap with mid-band spectrum, meaning that it can be appropriate for less densely populated areas that would normally be assigned to mid-band spectrum.

5G NR mmWave also supports carrier aggregation and PDCP split bearer functionality in the uplink direction, meaning consumers can send data at even higher data speeds.

In June 2020, we published a *Signals Ahead* report that looked at uplink mmWave performance. At the time we did this study, the network and smartphone were limited to a single 100 MHz uplink channel so as part of the research for this paper we conducted some additional tests to quantify the use of 2x100 MHz of uplink spectrum. We include results from both test campaigns in this section.

Figure 23 provides a geo plot of the uplink data speeds along the route that we used in downtown Minneapolis. These results stem from the second time we walked this route. The colored arrows identify the locations of the 5G NR mmWave radios and the directions the radios pointed. Given the route we took in this test we didn't connect to all the 5G NR mmWave radios in the area. Conversely, there were some areas along the walk where there wasn't any mmWave coverage.

Figure 23. mmWave Uplink Data Speeds – geo plot

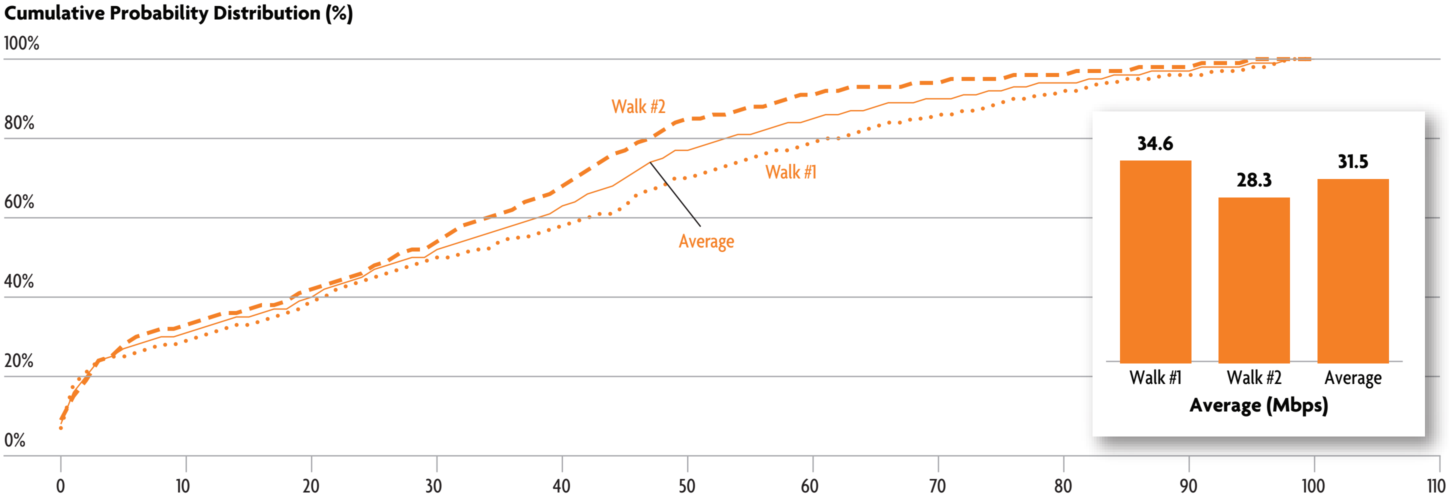


Source: Signals Ahead Vol 11, June 2020

The average data speed for the two tests was 31.5 Mbps with a peak uplink data speed of 98.3 Mbps.

Figure 24 shows the distribution of uplink data speeds from the two tests as well as the average uplink data speeds. The average data speed for the two tests was 31.5 Mbps with a peak uplink data speed of 98.3 Mbps. The uplink data speed exceeded 28 Mbps for 50% of the time. 5G NR mmWave is TDD-based with the same radio channel used for downlink and uplink transmissions. Since the bandwidth targets the downlink direction where most mobile data traffic occurs, the TDD slots are only serving the uplink direction for approximately 30% of the time. This point, along with the use of a single 100 MHz channel for uplink data traffic versus 400 MHz for downlink data traffic (800 MHz as shown earlier in this paper) provides some context into the uplink data speeds compared with what we frequently observe in the downlink direction.

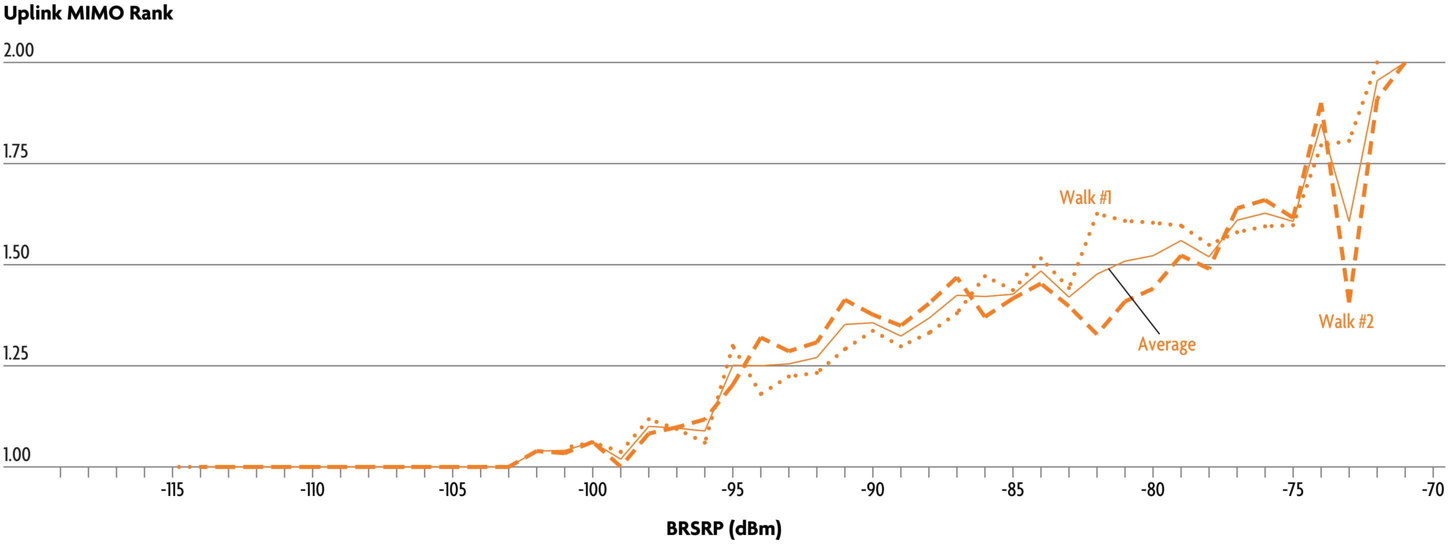
Figure 24. mmWave Uplink Data Speeds – distribution and average



Source: Signals Ahead Vol 11, June 2020

One interesting attribute of uplink 5G NR mmWave is that it uses MIMO to help increase data speeds when the channel conditions are suitable. LTE does not currently support uplink MIMO. Figure 25 shows the relationship between the downlink signal strength (Beam-RSRP) and uplink MIMO. As one might expect, uplink MIMO utilization improved with higher/better BRSRP.

Figure 25. Uplink MIMO Rank Versus BRSRP

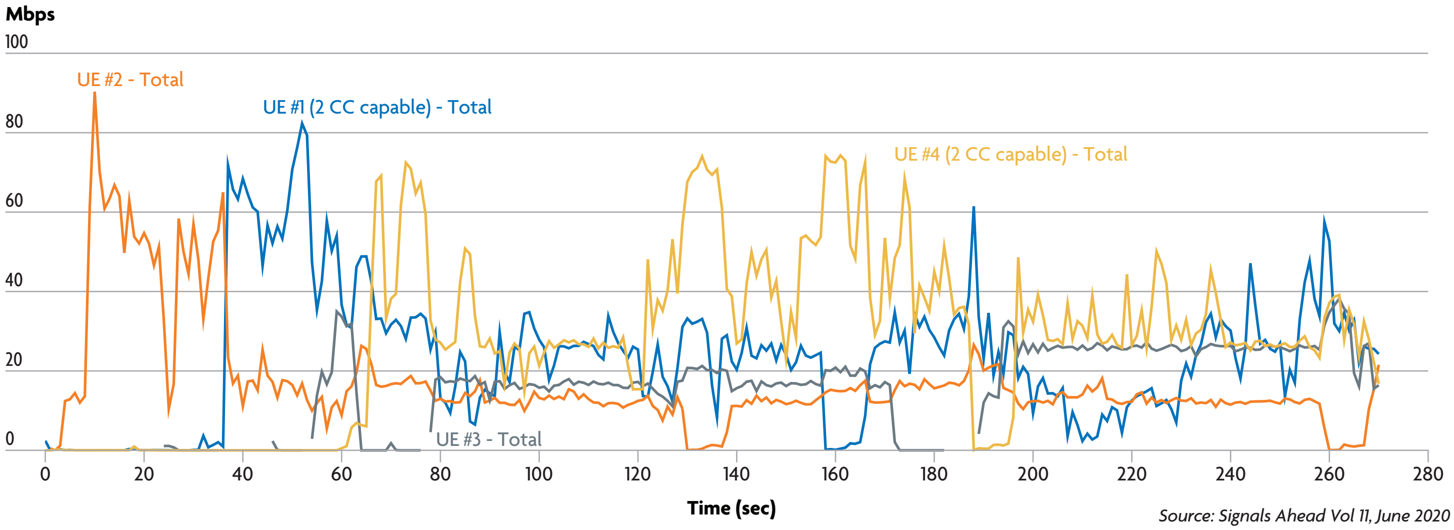


Source: Signals Ahead Vol 11, June 2020

When we were in Chicago testing 8CC we also tested 2CC uplink capabilities which our S 20 Ultra smartphones supported. The last two figures in this section highlight typical results from this testing, which compared 2CC uplink with 1CC uplink. In this test, we used four smartphones. UE #1 and UE #4 supported 2CC (2x100 MHz) uplink. UE #2 and UE #3 only supported 1CC (1x100 MHz) uplink.

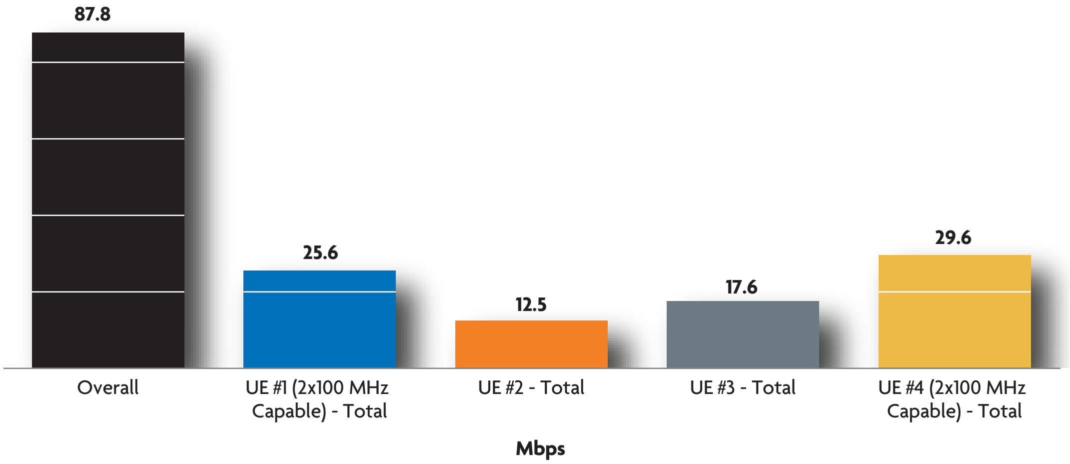
As shown in Figure 26, we started the uplink data transfer on each device separately so at the start of the test, UE #2 (1CC) achieved the highest uplink data speeds of all smartphones during the test. The dips down to ~0 Mbps for all smartphones reflect those times when the test scenario for that smartphone finished and prior to the next uplink data transfer session starting. The period that is most interesting is between approximately 60 seconds and the end of the test when all four smartphones were almost always transmitting data in the uplink. Figure 27 shows the average uplink data speeds for the four smartphones during this period of the test. As shown in the figure, the two smartphones which supported 2CC uplink achieved nearly twice the uplink data speeds of the two smartphones which only supported 1CC uplink. Lastly, we note that the network wasn't configured for PDCP split bearer combining so the uplink data speeds could have been even higher with the simultaneous use of one or more LTE radio channels.

Figure 26. Uplink Throughput Time Series Plot – by device



Source: Signals Ahead Vol 11, June 2020

Figure 27. Average Uplink Throughput – by device



Source: Signals Ahead Vol 11, June 2020

We anticipate the eventual support for 3CC uplink or even more uplink radio bearers along with the commensurate boost in uplink data speeds.

5G NR mmWave will always disproportionately favor the downlink direction since the bulk of today's data traffic is in the downlink direction. However, the uplink mmWave data speeds more than suffice for most use cases with this statement being even more true with 2CC uplink and uplink PDCP split bearer combining. We anticipate the eventual support for 3CC uplink or even more uplink radio bearers. When this functionality is supported, we would expect a commensurate boost in uplink data speeds.

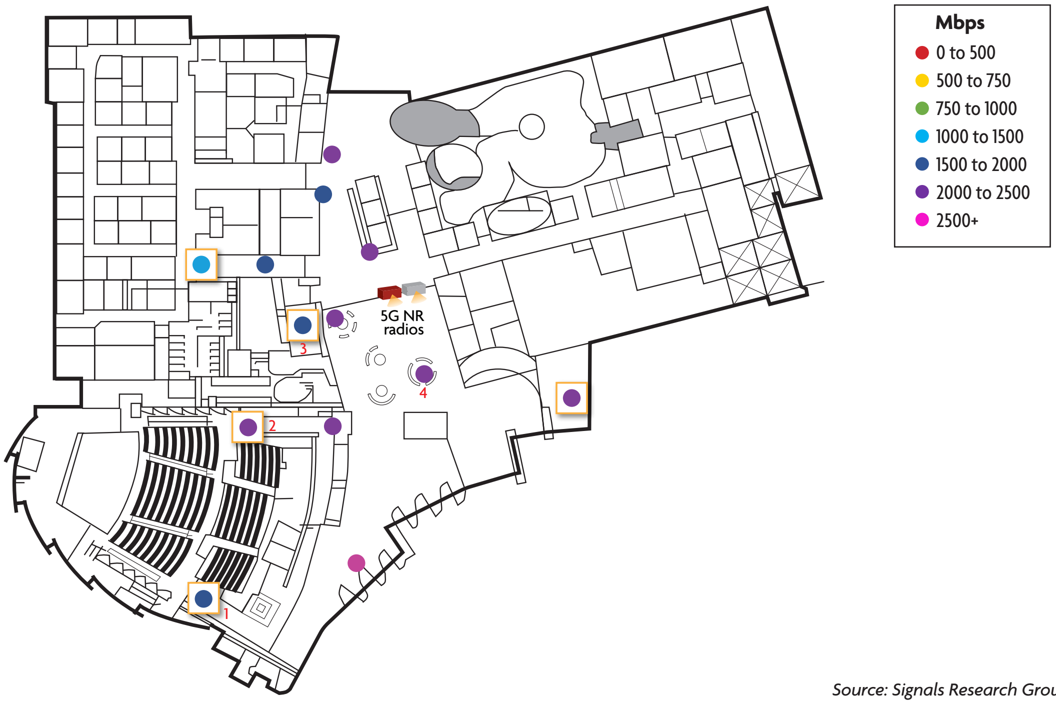
In-building deployments of 5G NR mmWave offer businesses and enterprises a compelling use case for offering high bandwidth wireless connectivity.

In late November 2020, we did in-building mmWave testing in Building N on the Qualcomm Campus in San Diego. We did in-building mmWave testing in 2019, but that testing was in a large venue – US Bank Stadium, which is home to the Minnesota Vikings. This in-building testing was much different since the venue was an enterprise (Qualcomm's HQ) so the location of the two mmWave radios and the overall layout of the building offered some interesting test conditions.

The two mmWave radios were mounted on a wall between the main and second floors in the atrium lobby of the building. Figure 35 includes a picture of the mmWave radios. We tested on the first and second floors of the building, including at locations with no visibility of the mmWave radios. Examples include the hallway entrance to the Irwin M Jacobs lecture hall, several locations in the lobby which were around the corner from the mmWave radios, and multiple locations directionally behind the mmWave radios, including in break rooms, down hallways, and even in a closed stairwell and conference room (pictures to follow).

To start things off, Figure 28 provides a plot of the average downlink throughput at multiple locations on the first floor. We've used rectangles to highlight those test locations with NLOS conditions. We were conservative when tagging the NLOS sites. For example, we didn't consider all the test locations behind the mmWave radios to be NLOS even though we couldn't physically see the radios since they were mounted on the opposite side of the wall from where we were standing with the radios positioned between the first and second floors. We revisit the numbering of some test sites later in this section when we show pictures of the test locations.

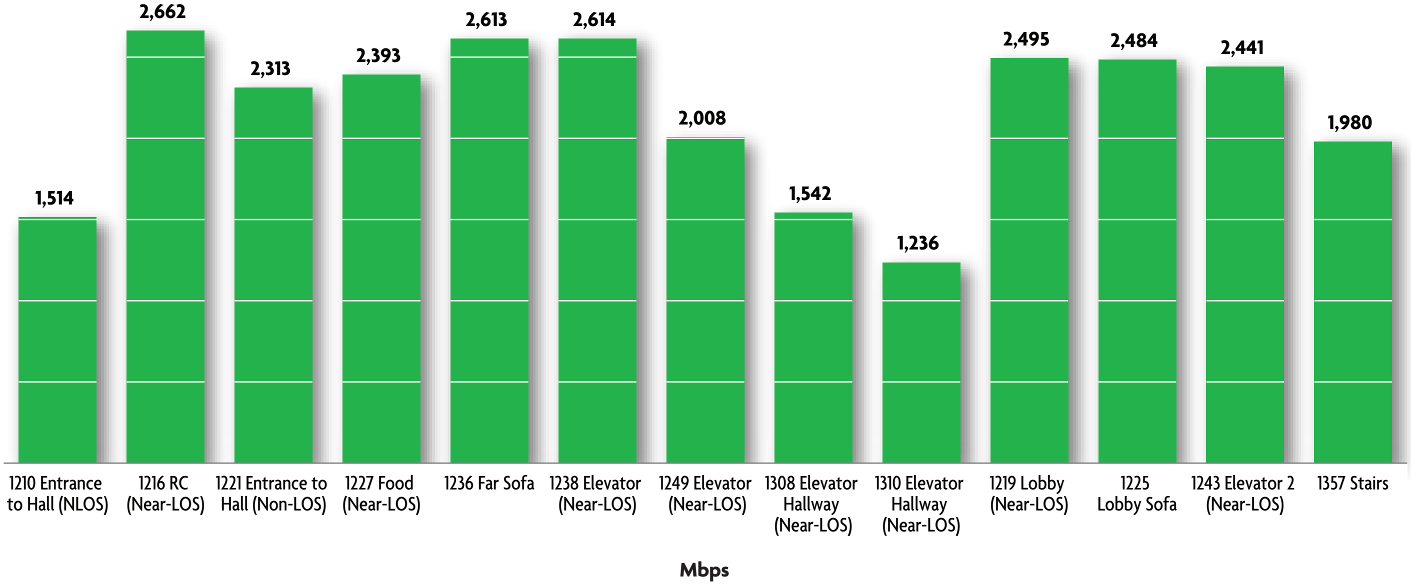
Figure 28. First Floor Downlink Throughput



Source: Signals Research Group

Figure 29 shows the average downlink throughput at each test location. We've labeled those locations which were NLOS and near-LOS as well as those sites which were behind the mmWave radios. It is also worth mentioning that we did these tests with a Galaxy Note 20 smartphone. When we used this smartphone in our Chicago testing it only supported 4CC. However, after an over-the-air firmware update the phone supported 8CC in these in-building tests.

Figure 29. First Floor Downlink Throughput



Source: Signals Ahead Vol 11, June 2020

As mentioned earlier in this paper, mmWave uses unique beam indices to improve the coverage and to minimize interference. Figure 30 shows the beam indices that we encountered during a walk test on the first floor, including behind the cell site and in the stairwell – each color represents a unique beam index. This information was interesting to us since we were curious to see which beams were used in the NLOS locations, like the stairwell, and where, or even if, these beams were used in the main atrium.

Figure 30. First Floor Beam Indices

Source: Signals Research Group

Figure 31 includes some pictures of a few test locations on the first floor. The numbering included in the labels matches with the numbering shown in Figure 28. The figure labeled "4 – Lobby Sofa" shows the two mmWave radios hanging on the wall.

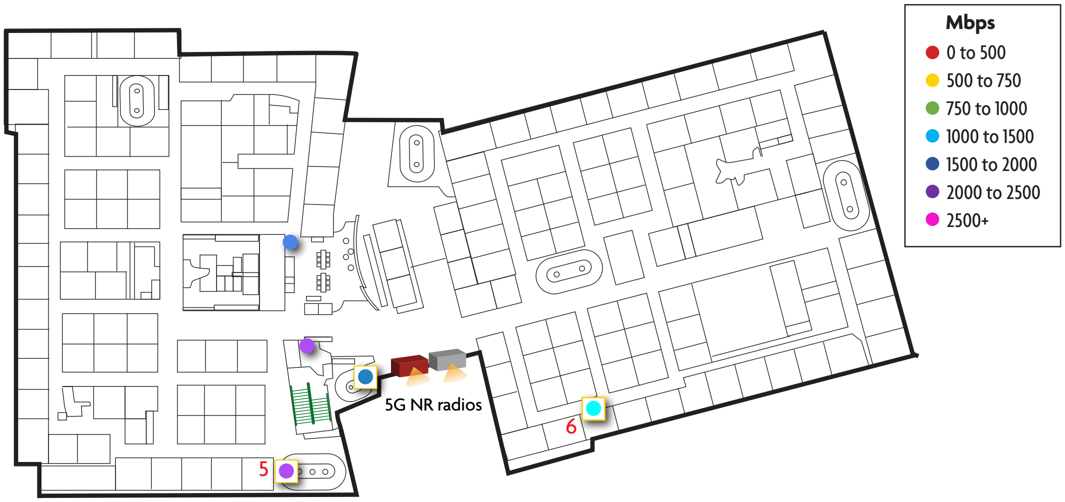
Figure 31. First Floor Pictures

1210 Entrance (Location 1) *1221 Entrance (Location 2)* *1225 gNB Sofa (Location 4)*

Source: Signals Research Group

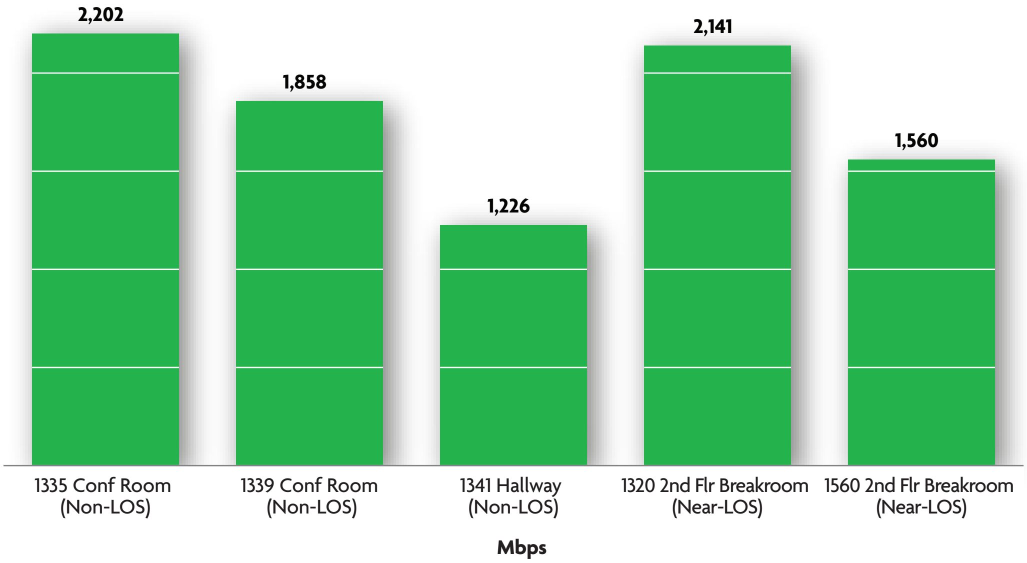
Figure 32 provides a geo plot of the average downlink throughput while testing on the 2nd floor and Figure 33 shows the average throughput at each location. We've highlighted those locations with NLOS conditions and the numbering matches with the images shown in Figure 35.

Figure 32. Second Floor Downlink Throughput



Source: Signals Research Group

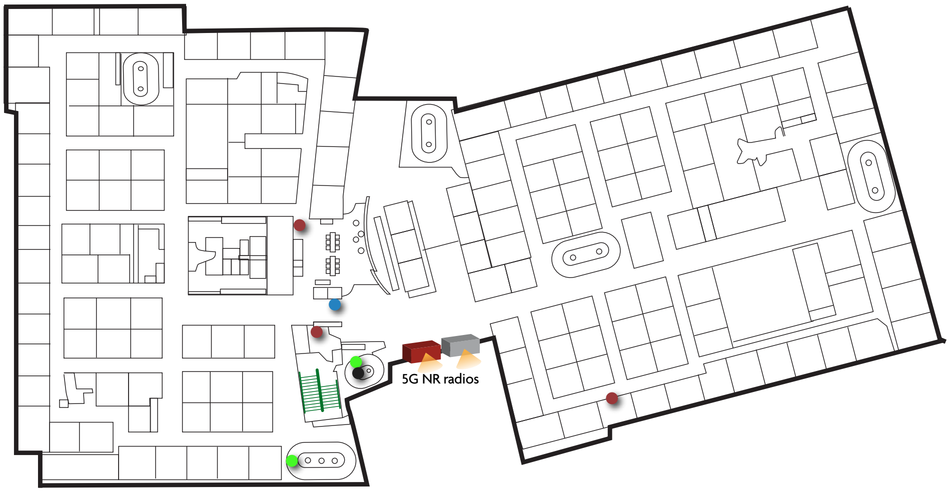
Figure 33. Second Floor Downlink Throughput



Source: Signals Research Group

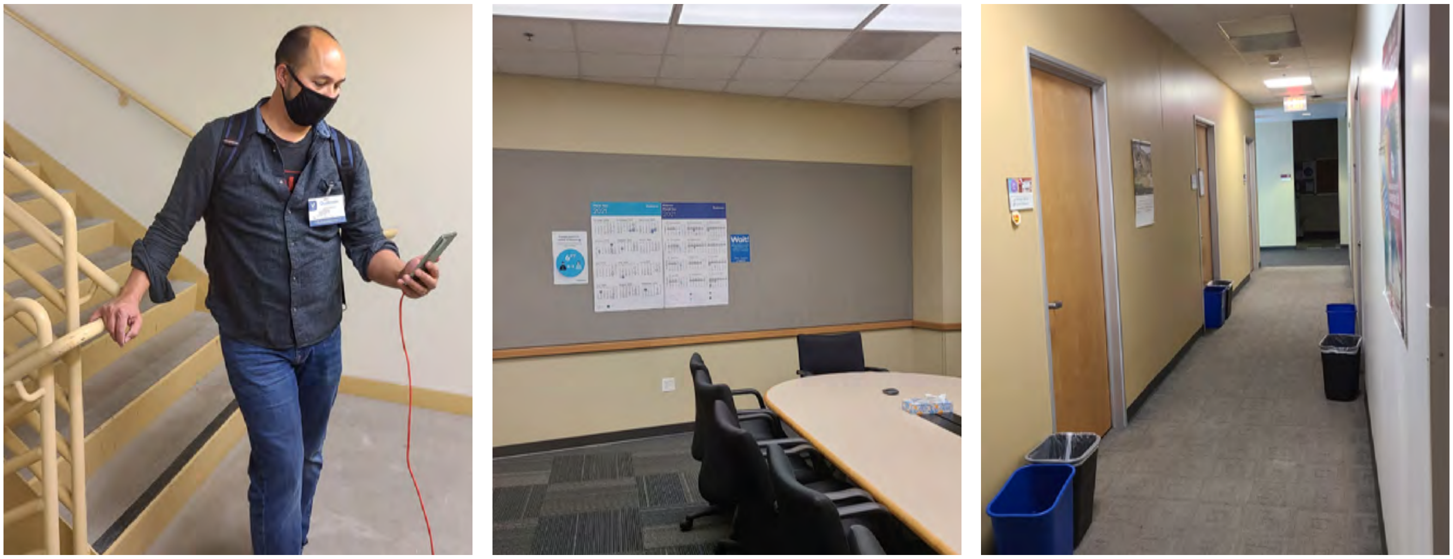
Figure 34 shows the unique beam indices at each test location. In one of the conference rooms, the smartphone used multiple beam indices during the test, so we included two unique colors at this location in the image. We also point out that in some of these NLOS locations we encountered beam indices that we never encountered on the first floor. Figure 35 includes pictures of a few test locations from the 2nd floor, including the stairwell between the first and second floors. The "2nd Floor Hallway" image shows a view of a hallway from where we stood when doing the test (average throughput = 1,226 Mbps). Someone would have to walk to the end of the hallway, turn right and walk some more, turn left and walk some more, and then look over the railing to see the mmWave radio pointed in the opposite direction. This description is also evident by viewing the floor plan in Figure 32 or Figure 34.

Figure 34. Second Floor Beam Indices



Source: Signals Research Group

Figure 35. Second Floor Pictures

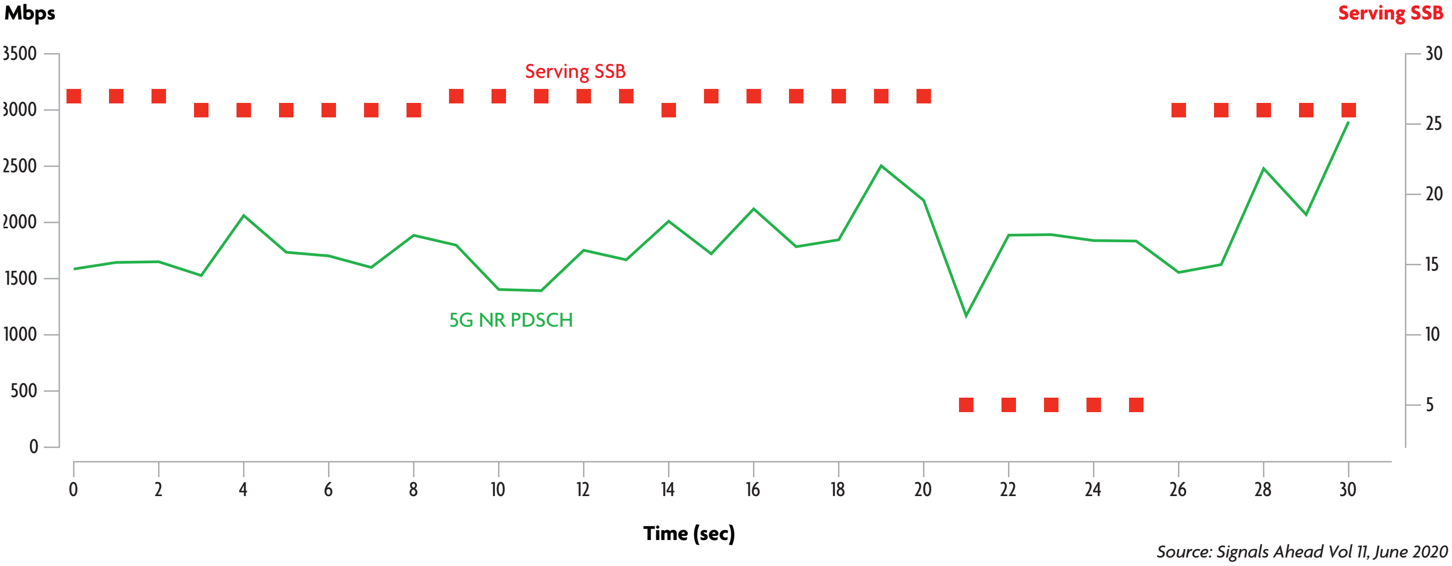


Stairwell (Location 3) ***Conference Room (Location 5)*** ***Second Floor Hallway (Location 6)***

Source: Signals Research Group

As mentioned in a previous paragraph, the smartphone could use different beam indices in some NLOS test locations. Figure 36 shows an example from testing in a 2nd floor conference room. The beam index changed multiple times during the test with no disruption in the downlink throughput.

Figure 36. Second Floor Conference Room Downlink Throughput and Beam Indices



Source: Signals Ahead Vol 11, June 2020

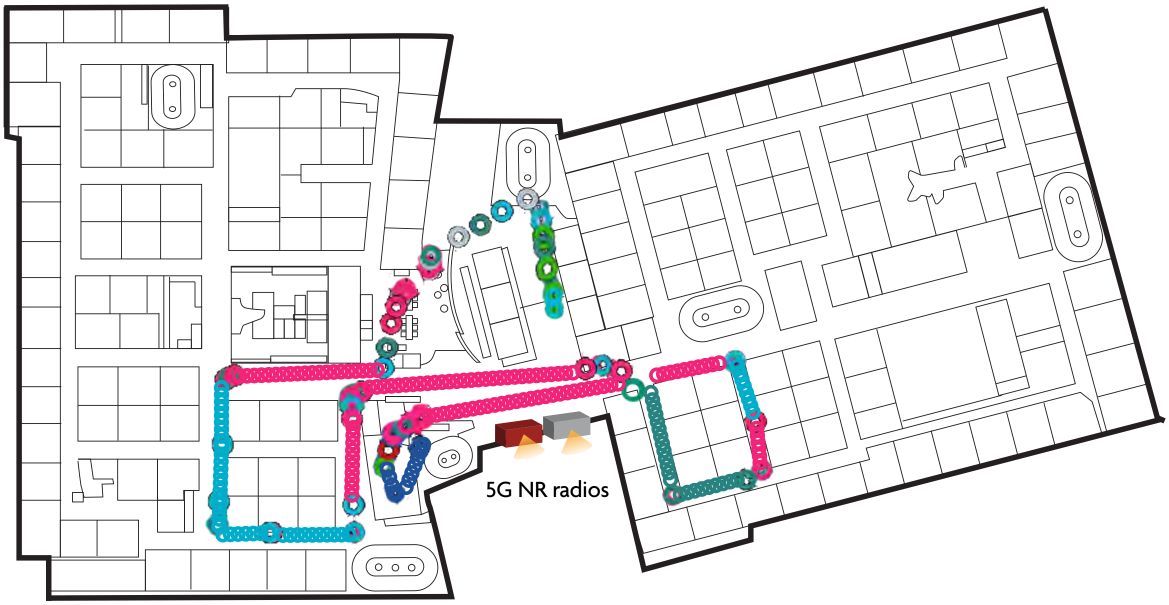
The mmWave signals found their way around corners, reflected off walls to provide coverage in the opposite direction, and snuck their way into conference rooms with the door closed.

In addition to logging chipset diagnostic messages, we also used the Rohde & Schwarz TSMA scanner to capture RF characteristics, including signal strength and signal quality for each detected beam index. Although we captured the data for the eight 100 MHz radio carriers that were present, we are only showing illustrations for three of the radio carriers. These results are representative of all eight carriers and they help demonstrate the behavior of mmWave signals in an enclosed environment.

Figure 37 shows the strongest beam index for three mmWave radio carriers while walking on the second floor. As previously noted, since the mmWave radios were mounted on the wall between the first and second floors, these radios, which pointed in the opposite direction, were never visible on the second floor. At some locations we could at least see the balcony immediately above where the radios were mounted while at other locations, we couldn't even see the balcony. In this figure, each colored circle represents a different beam index. It is evident that different beam indices provided coverage in different parts of the building, plus it is evident that the top (strongest) beam index at a given location was not always the same for each radio carrier.

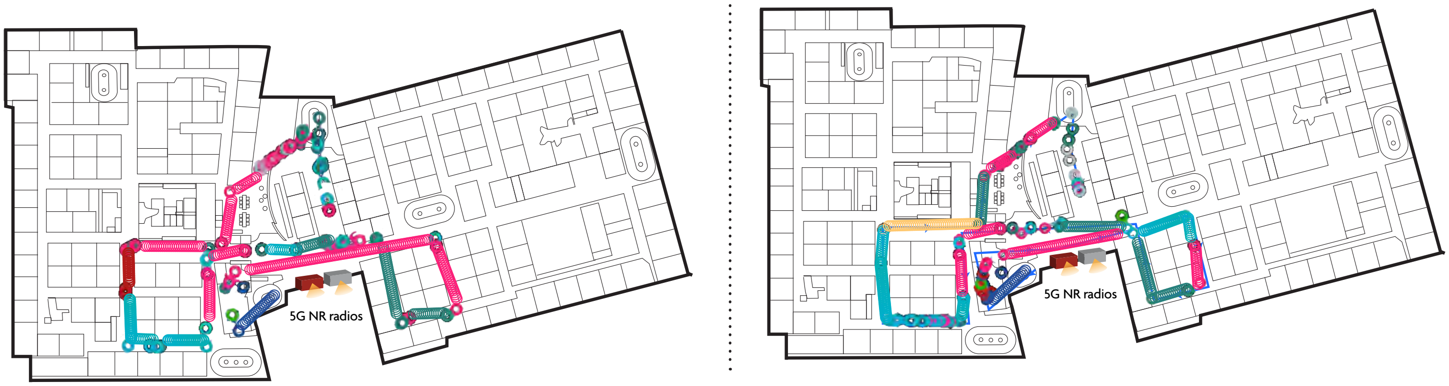
Figure 37. Top Beam Index by Radio Carrier

EARFCN = 2080731



EARFCN = 2082395

EARFCN = 2084059



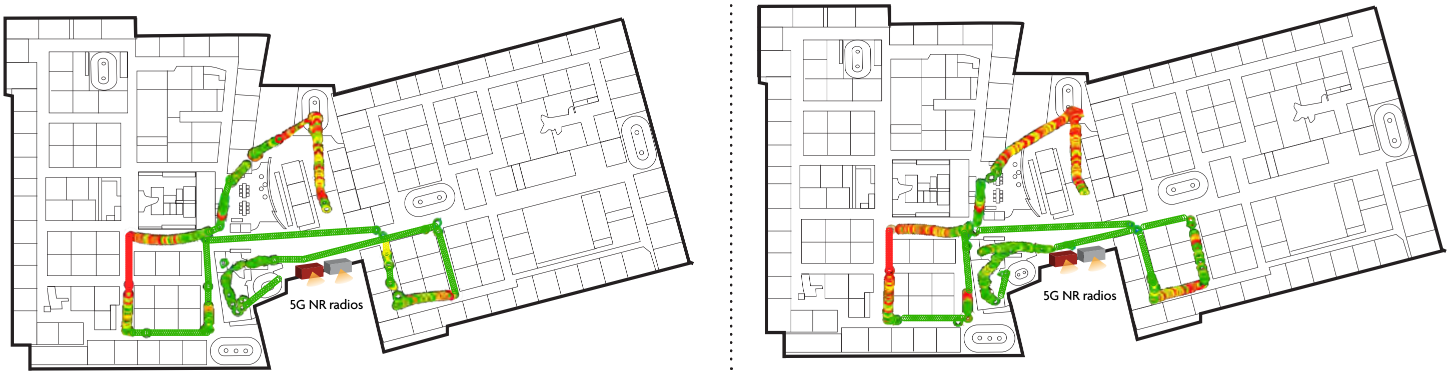
Source: Signals Research Group

Figure 38 shows the signal quality (Beam SINR or BSINR) for the three radio carriers, based on the BSINR for the beam index identified in the previous figure. The figure shows NLOS locations where the signal quality was still good, including along the hallways to the right of the mmWave radios and in the enclosed conference rooms. In portions of the hallway to the left of the radios and in the back of the building the signal quality was not as good. Another observation is that the signal quality varied between the three radio carriers at some locations along the route. This phenomenon is characteristic of mmWave and how it behaves, even though this behavior is not obvious with normal smartphone usage.

Figure 38. Signal Quality by Radio Carrier

EARFCN = 2080731

EARFCN = 2082395 ***EARFCN = 2084059***



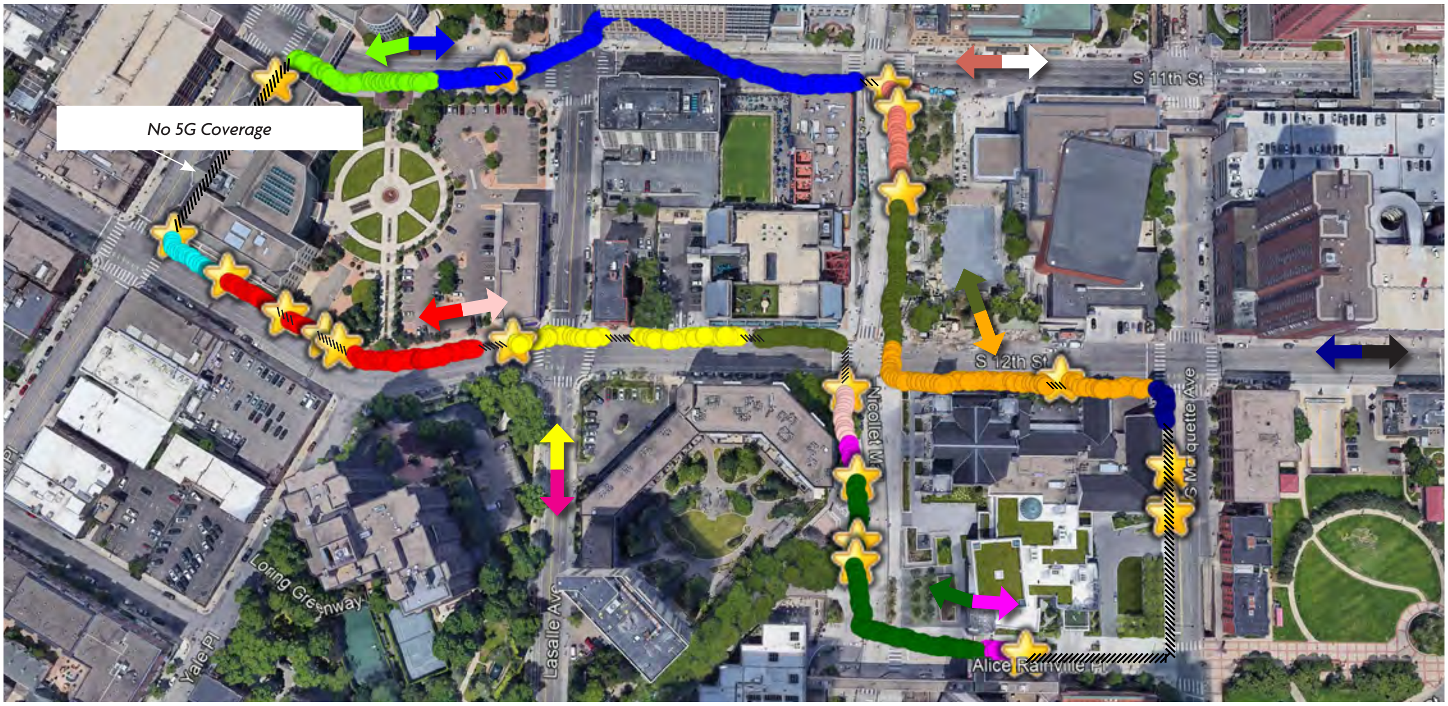
Source: Signals Research Group

Our key takeaway from the in-building testing is that mmWave coverage is achievable in an enterprise without requiring a densely deployed cell grid and LOS views of the mmWave radio. In this building, there were only two collocated mmWave radios so there obviously wasn't ubiquitous coverage throughout the entire building. However, given our experience and the test results shown in this section, it seems apparent that it wouldn't require a massive deployment of mmWave radios to achieve excellent coverage throughout much of the building. The mmWave signals found their way around corners, reflected off walls to provide coverage in the opposite direction, and somehow snuck their way into conference rooms with the door closed.

5G NR mmWave continues to be more resilient to ground clutter than generally perceived.

To wrap up this paper, we'd like to return to the uplink testing we did in Minneapolis for the Signals Ahead report we published in June. In the previous section we demonstrated the resiliency of mmWave signals in an in-building deployment. In this section, we further demonstrate this resiliency in a multi-cell outdoors cluster. The next several figures stem from the same tests that we showed in the uplink section of this paper. However, the figures in this section show different information.

Figure 39. Serving Cell PCIs During Walk Test



Source: Signals Ahead Vol 11, June 2020

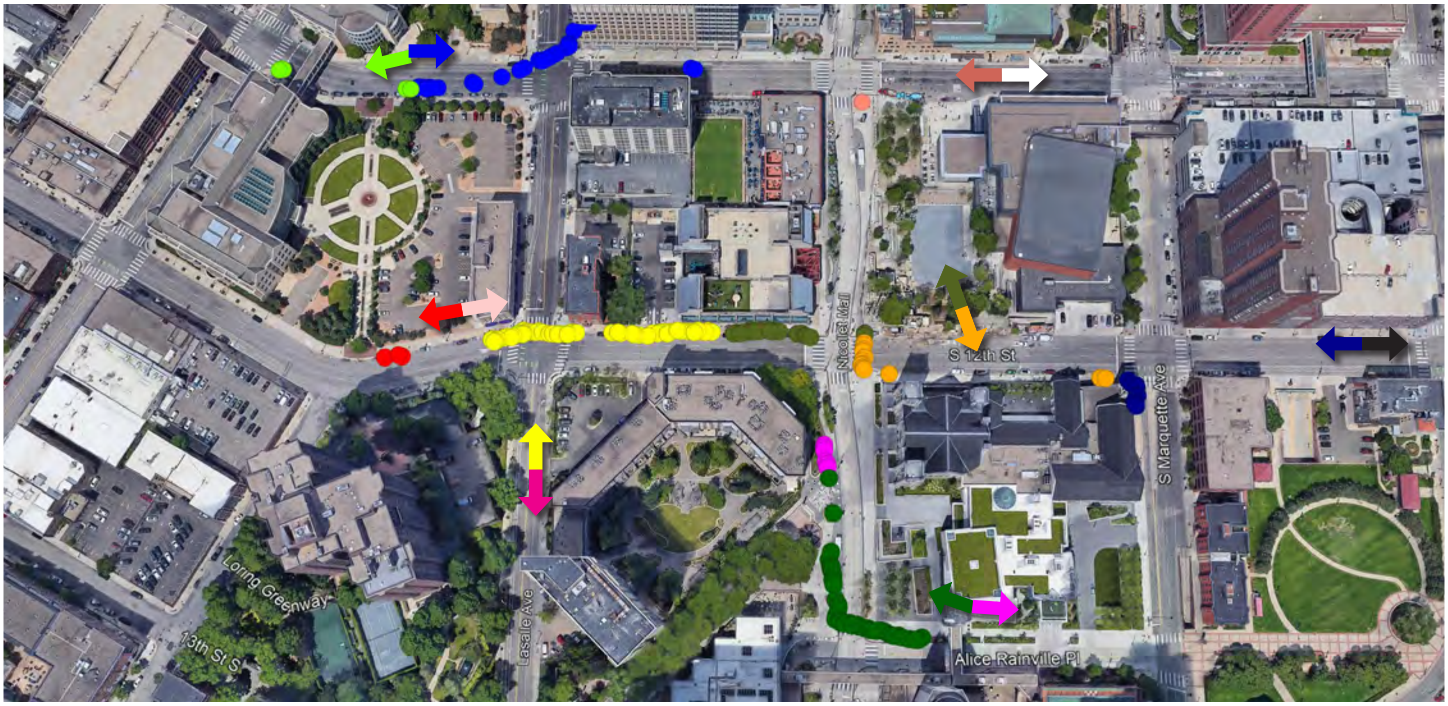
Figure 39 includes three important pieces of information. Each colored arrow identifies the location of a 5G NR mmWave radio – there were two radios at each location facing in opposite directions. The colored circles along the route identify each 5G NR mmWave cell PCI that we used. These colors map to the colored arrows, meaning where there is a red circle, the smartphone was attached to the 5G NR mmWave radio depicted by the red arrow. Since we didn't walk everywhere there was 5G NR mmWave coverage it is evident the smartphone didn't attach to all the 5G NR mmWave radios in the area (e.g., there is a white arrow but no white circles). Lastly, the stars indicate places along the route where the LTE PCI providing the LTE anchor changed. With the NSA architecture that is used today there needs to be an LTE anchor. The somewhat surprising observation is the frequency of the LTE handovers within a relatively small area. Generally, the smartphone used an "obvious" 5G NR PCI, but there are some interesting points worth highlighting.

- When the smartphone was in front of the off-pink arrow in the lower left corner, the smartphone was attached to the yellow arrow coming from a perpendicular street. Further along the route while walking south on Nicollet Mall the smartphone attached to the off-pink arrow.

- The magenta arrow in the lower right corner points directly into a glass window of an enclosed Skyway that encompasses the city. This fact explains why there are magenta circles "behind" the magenta arrow (reflections) and why there aren't any magenta circles in front of the magenta arrow (blockage).

Figure 40 shows the same information as the previous figure. However, the figure only includes those locations where there were at least two 5G NR mmWave radios providing coverage to the location. Specifically, we used chipset diagnostic messages to identify when the smartphone's measurement reports from non-serving cells had a signal strength of at least -105 dBm. Figure 40 still identifies the serving cell PCI (colored circles) while Figure 41 shows the cell site PCI with the second strongest signal strength (BRSRP > -105 dBm).

Figure 40. Serving Cell Coverage with Multiple Cells Providing Adequate Coverage

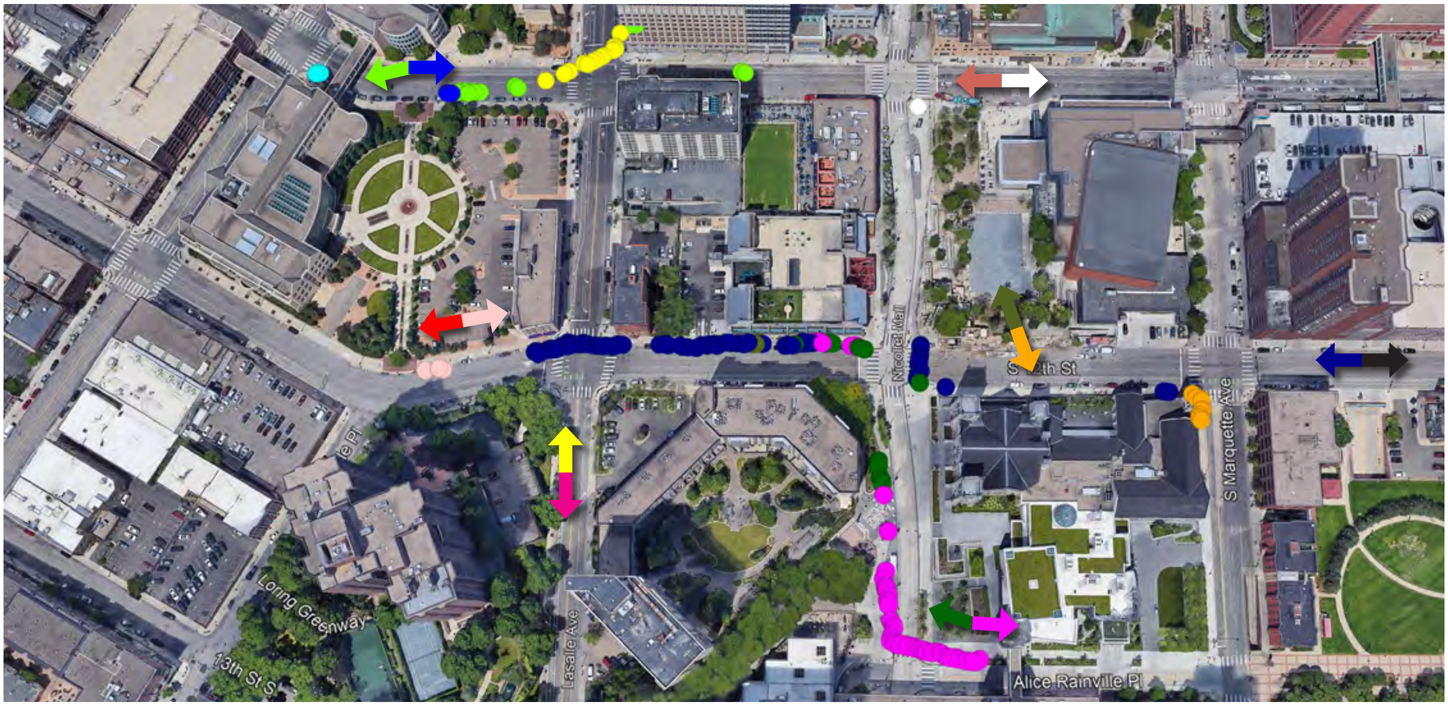


Source: Signals Ahead Vol 11, June 2020

Comparing these two figures, we can make a few observations.

- The magenta arrow reflecting off the Skyway provided meaningful coverage in the opposite direction. The smartphone didn't connect to this PCI since the signal strength from the Dark Green arrow was much stronger.
- The 5G NR cell site with the dark blue arrow provided adequate coverage more than two blocks beyond its location – again there were other 5G NR mmWave cell sites in the area that provided a stronger signal, so the smartphone didn't need to use the more distant cell site.
- The cell site with the light green arrow provided momentary coverage one block in the direction opposite from the direction the radio was facing.

Figure 41. Second Strongest PCIs (BRSRP > -105 dBm)



Source: Signals Ahead Vol 11, June 2020

Although we are not including the figures in this whitepaper, we identified a few locations along this same route when there were up to four mmWave radios providing coverage to the same spot.

Test Methodology

In our 5G benchmark studies, we leverage test and measurement equipment from our trusted partners to conduct rigorous analysis of device and network performance. We capture chipset diagnostic messages from the modem(s) in the smartphone which provide information on literally hundreds of network parameters up to one thousand times per second. With this information, including layer 1, layer 2, and layer 3 signaling messages, we can analyze how the network and the phone are communicating with each other – which radio bearers are being used, how network resources are being allocated, the utilization and efficiencies of MIMO transmission schemes, and the quality of the radio conditions, to name a few. We also use network scanners to independently verify radio conditions from the serving cell as well as from adjacent cells. Scanner information serves as a great complement to device/chipset information and it is captured even when the smartphone can't connect to the network – for example, if the 5G signal is too weak. Finally, we use high bandwidth dedicated servers to generate reliable and sustained data transfers when doing our tests.

We've worked with Accuver Americas since we did our first LTE benchmark study in 2009. We use the company's XCAL-M and XCAL-Solo drive test tools to capture the diagnostic messages from the modem(s) in the smartphone. XCAL-Solo is a handheld unit that makes it relatively easy to walk around a city or stadium while testing and it is an invaluable tool when testing millimeter wave performance. And with the solution's in-building mapping capabilities, we were able to collect and map the results that we obtained with our enterprise tests. Accuver Americas has also integrated its solutions with the Rohde & Schwarz scanners that we have used in our studies. We also use the company's XCAP post-processing software to analyze the chipset and scanner logs that we captured.

Our collaboration with Spirent Communications goes back to 2006 when we did the industry's first independent benchmark studies of 3G chipsets. We are currently using the company's Umetrix Data platform to generate high bandwidth data transfers during our tests. We also used the Umetrix video platform when doing video quality analysis included in this study.

We've also used various Rohde & Schwarz scanners for *Signals Ahead* studies as well as for commissioned projects that we've done in recent months. We leveraged the company's TSMA autonomous drive test scanner, which contains the TSME ultra-compact drive test scanner and an integrated PC when we did the industry's first 5G millimeter wave benchmark study back in January 2018. This solution fits into a self-contained backpack, thereby allowing us to walk the streets of Houston where Verizon had deployed its trial network.

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