CAP'N CRUNCH

HOW 5G NR MILLIMETER WAVE (mmWave) PROVIDES CRITICAL ADDITIONAL NETWORK CAPACITY IN INDOOR VENUES AND OUTDOOR ENVIRONMENTS, EVEN IN THE PRESENCE OF LTE AND MID-BAND 5G NR

January 2022

Prepared by
Signals Research Group

SiGNALS Research Group
www.signalsresearch.com

We conducted this benchmark study on behalf of Qualcomm Technologies, Inc. SRG was solely responsible for collecting and analyzing the drive test data presented in this report. We collected the results in commercial networks with commercial smartphones in September and October 2021. The comments provided in this whitepaper are based on our analysis of the data, which is also included to the maximum extent possible in this paper.

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

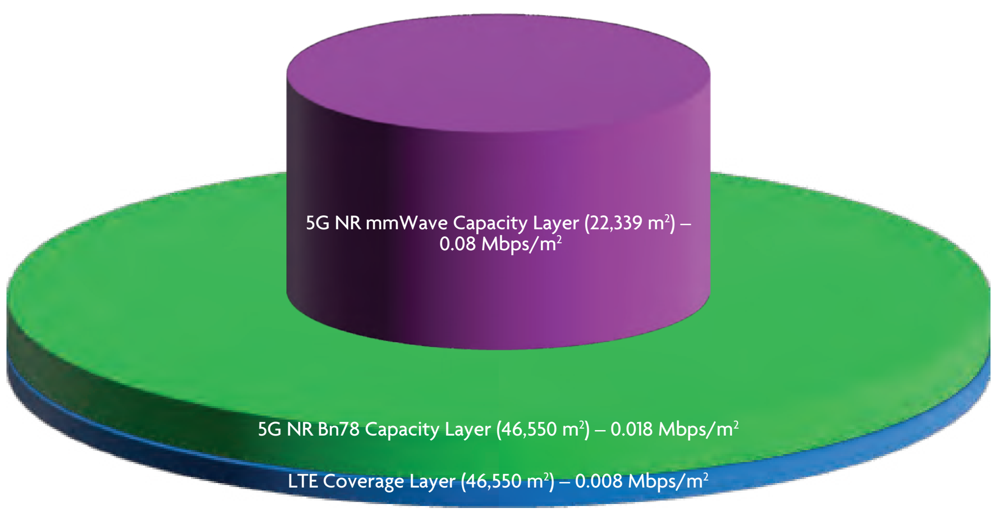
1.0 Executive Summary

Signals Research Group (SRG) conducted a benchmark study to quantify the incremental benefits of 5G NR mmWave when deployed in an operator's existing network, including a network which also supports mid-band 5G NR. This study is highly unique relative to earlier studies we have done since it incorporated a large number of mobile devices to quantify system-level performance with LTE, mid-band 5G NR, and 5G NR mmWave. In addition to determining the capacity thresholds for each network technology, we incorporated user experience metrics related to video performance to demonstrate how 5G NR – both mid-band and mmWave – improve the user experience in a congested network.

For this study, we tested at the Footprint Center, home to the Phoenix Suns NBA team, in Phoenix, AZ using the Verizon Wireless network. We used up to 17 Samsung Galaxy S20 smartphones with the Snapdragon® 865 5G Mobile Platform to determine the potential downlink and uplink capacity of the operator's LTE network and then the additional capacity 5G NR mmWave provided. We also tested in an outdoor area in central Helsinki, Finland on the Elisa network which included LTE, 5G NR Bn78 (3.5 GHz) and 5G NR Bn258 (25 GHz or mmWave). In this network we leveraged up to 20 Asus smartphones for Snapdragon Insiders with the Snapdragon 888 5G Mobile Platform. Our objectives when testing this network were similar to our objectives when testing the Verizon network. Two key differentiators with the second study were that it involved an outdoor venue that has high traffic volumes on a daily basis and that the network was located in Europe. 5G NR mmWave is no longer a US centric story.

We tested 5G NR mmWave performance at the Footprint Center (Verizon Wireless) in Phoenix, AZ and around an outdoor plaza in central Helsinki, Finland (Elisa).

Figure 1. LTE and 5G NR Capacity Densities



Source: Signals Research Group

Key highlights from our benchmark study, which we validate with supporting data in this whitepaper, include the following:

- Despite the enhanced efficiencies of LTE networks, there is a breaking point in the amount of data traffic these networks can support. When testing both venues, we calculated the LTE spectral efficiency for downlink data traffic was between 5-7 bps/Hz with the uplink spectral efficiency approximately half what we observed in the downlink direction.

- When combined with the somewhat limited amount of spectrum available for LTE services, we observed reduced downlink/uplink data speeds, even with the small number of smartphones we used in our tests. The lower throughput had a noticeable impact on the user experience when live streaming video content (uplink) or viewing video content (downlink).
- We documented at least a 10x increase in the downlink total throughput versus LTE and at least a 2x increase in the uplink total throughput versus LTE after enabling 5G NR mmWave on the smartphones. Individual user data speeds (per smartphone) can increase even further, thanks to the use of PDCP combining, which allows the simultaneous transmission of data content over both networks.
- With 5G NR mmWave enabled on the smartphones, the video performance (downlink and uplink) improved substantially. In addition to eliminating video freezes and impairments, there was an overall increase in sector throughput, which can benefit all consumers, even consumers without a 5G NR mmWave smartphone.
- In uplink tests, involving different numbers of smartphones supporting 5G NR mmWave + LTE or LTE only, we observed those smartphones with 5G NR mmWave functionality had, on average, uplink data speeds up to 3.7x higher than those smartphones which only supported LTE. Since we did this test, we've had the opportunity to witness a pre-commercial smartphone use four 100 MHz mmWave channels, which substantially increases the uplink throughput over what we observed in the results obtained for this study.
- The benefits of deploying 5G NR mmWave also apply to operators with mid-band 5G NR networks. We documented a 4.4x increase in the "capacity density" due to 5G NR mmWave deployed within a mid-band 5G NR network. By our definition, the capacity density quantifies the total throughput (Mbps) delivered across a target area (m^2).
- 5G NR mmWave coverage is surprisingly robust and it doesn't necessarily require significantly higher cell densities, compared to the existing cell grid. In an indoor venue, 5G NR mmWave coverage is nearly ubiquitous in the areas where it is intended to provide coverage. This outcome isn't surprising given the line-of-site conditions and the close confines of the coverage area (e.g., a basketball arena or football stadium).
- In an outdoor deployment, operators will deploy 5G NR mmWave in high traffic areas where the cell densification is already significant. A one-for-one overlay won't necessarily provide ubiquitous mmWave coverage, but it goes a long way toward providing significant capacity over much of the targeted coverage area.

Figure 1 shows the traditional layered cake that the industry likes to use when describing coverage and capacity layers in an operator's network. In the "old days" the lowest layer was GSM, the mid layer was EDGE, and the highest layer was UMTS/HSPA – the highest layer because no one at the time envisioned an operator deploying widespread 3G network coverage using 2.1 GHz. The layered cake concept isn't new, but our rendition is very differentiated since it was drawn to scale, based on network testing we did in the Elisa network. The figure emphasizes two important points worth highlighting:

- In high traffic areas, the existing LTE cell grid is dense enough to support a one-for-one 5G NR mid-band deployment with nearly identical coverage, especially with respect to outdoor coverage. 5G NR in Bn78 (100 MHz channel bandwidth) also more than doubled the available network capacity (2.3x versus the 2x60 MHz of LTE spectrum).

- 5G NR mmWave coverage from the same location as the LTE and 5G NR mid-band radio assets didn't match the LTE coverage, but it covered much of the same sector, in particular the outdoor areas. More importantly, it delivered a 10.1x increase in capacity over LTE (4.4x versus Bn78). Offloading traffic onto 5G NR mmWave also frees up network resources for those smartphones that don't support 5G NR mmWave or are located outside of mmWave coverage. The 5G NR mmWave capacity shown in the figure is based on a more conservative value that stems from our study. If we had used the higher number that we also obtained, the 5G mmWave capacity density would have been higher than shown.

The remaining chapters in this whitepaper discuss our results and analysis in much greater detail. Chapter 2 provides a short introduction to Signals Research Group. Chapter 3 contains results from our testing in Phoenix and Chapter 4 contains results from testing in Helsinki. Finally, Chapter 5 includes our test methodology, which we used to collect the network performance data and to analyze the video performance.

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2.0 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. Including that initial study, we've conducted twenty 5G NR benchmark studies through November 2021. 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 two 5G NR reports on Dynamic Spectrum Sharing (DSS – Dec 2020 and Mar 2021), a report on mid-band 5G NR performance in Europe (Nov 2021), as well as a report on critical uplink enhancements (uplink-256QAM and uplink-MIMO) that operators and vendors are just beginning to introduce (Aug 2021).

For this paper, we conducted additional testing that was specific to the objectives of this study. We tested at the Footprint Center, home to the Phoenix Suns NBA team, in Phoenix, AZ using the Verizon Wireless network, which supported five different LTE bands as well as 5G NR mmWave using Bn261 (28 GHz). We also tested in Helsinki, Finland on the Elisa network which includes support for three LTE bands, 5G NR Band n78 (3.5 GHz) and 5G NR Band n258 (25 GHz or mmWave). Both operators provided critical logistical support, but they had no active role in how we tested or analyzed the data. As a courtesy, we provided both operators with a preview of our findings from testing their respective networks.

Thanks to our test and measurement partner companies that we used in this study, Accuver Americas and Spirent Communications, 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.

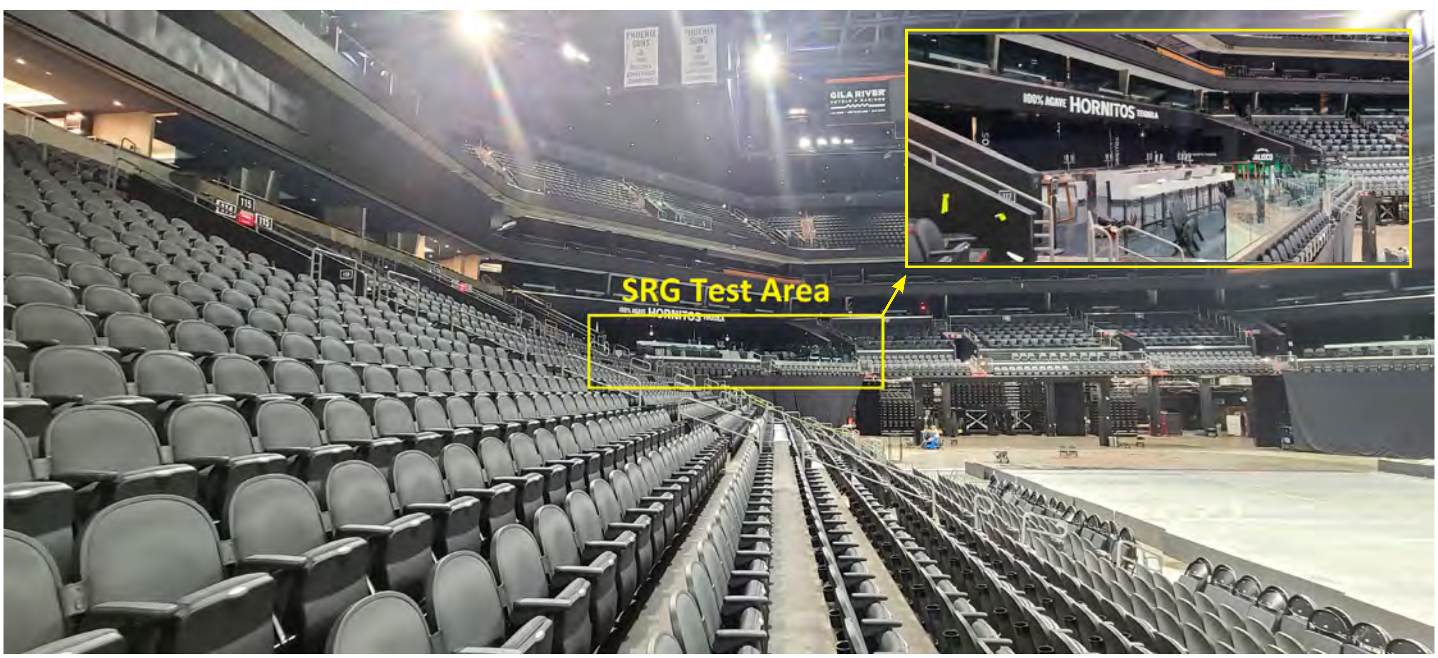
One key differentiator for this study is that we leveraged a large number of smartphones when collecting the performance data in the two networks. Specifically, we used up to 17 Samsung Galaxy S20 smartphones (Snapdragon 865 5G Mobile Platform) in the Verizon network and up to 20 Asus smartphones for Snapdragon Insiders (Snapdragon 888 5G Mobile Platform) in the Elisa network. By leveraging a large number of smartphones operating in the same LTE/5G NR sector, we were able to quantify network-level performance characteristics in a loaded network, not to mention differences in performance across all smartphones, which used different LTE band configurations and/or 5G NR. This type of analysis is not possible while testing with a single smartphone.

3.0 5G NR mmWave in a Large Indoor Public Venue in North America

We tested at the Footprint Center in Phoenix Arizona during the week of September 26th. Specifically, we tested in and around one of the refreshment areas within the venue where fans go to imbibe on their favorite beverage. This area represents an ideal test location since it is a high traffic area during a live event and there was easy access to electrical outlets and places to locate our test laptops and smartphones. We used four laptops, each with four smartphones attached (sixteen total smartphones), with these laptops spread throughout the refreshment area. There was an additional laptop and smartphone that we used for our video testing. We also used lengthy USB cables to further separate the smartphones from each other. Figure 2 shows a picture of the test area. The inset shows the location of four laptops, including the laptop we used for the video testing. The fifth laptop is located in the far corner of the bar, and it is not visible in this picture.

Inside the venue, Verizon had 60 MHz of LTE spectrum. This spectrum includes two different channels in Band 66 and two different channels in Band 5. We've labeled them Band 66 / Band 66 II and Band 5 / Band 5 II in this report. The LTE network supported up to four carriers, as well as 800 MHz of 5G NR in Band n261 (28 GHz). Although the network supported PDCP combining between 5G NR and LTE, we only observed PDCP combining in the uplink direction. Likewise, although the network supported 2x100 MHz in the 5G NR uplink, the network didn't trigger this feature in most cases, so the uplink throughput was typically limited to a single 100 MHz 5G NR uplink channel. If anything, the results in this paper understate the 5G NR uplink capabilities as well as the total user throughput with 5G NR and LTE combined in the downlink direction.

Figure 2. SRG Test Area at Footprint Center



Source: Signals Research Group

LTE Bands – Single Radio Sector

- Band 2 (2x5 MHz)
- Band 66 (2x15 MHz and 2x10 MHz)
- Band 5 (2x10 MHz and 2x10 MHz)
- Band 13 (2x10 MHz)

5G NR Band – Two 5G NR Radios

- Band n261 (8x100 MHz) – roughly 80/20 DL/UL ratio

Lastly, we note the area where we tested had coverage from a single LTE radio sector and two different 5G NR radios. The LTE coverage from this radio sector and from each of the two 5G NR radios extended beyond our test area but for purposes of this study we are most interested in the total capacity within the refreshment area where we tested. Whenever possible, we identify the amount of data traffic going on each 5G NR radio and on each LTE band, as well as how the total bandwidth was distributed between each smartphone.

3.1 LTE and 5G NR mmWave Total Capacity and Individual Data Speeds

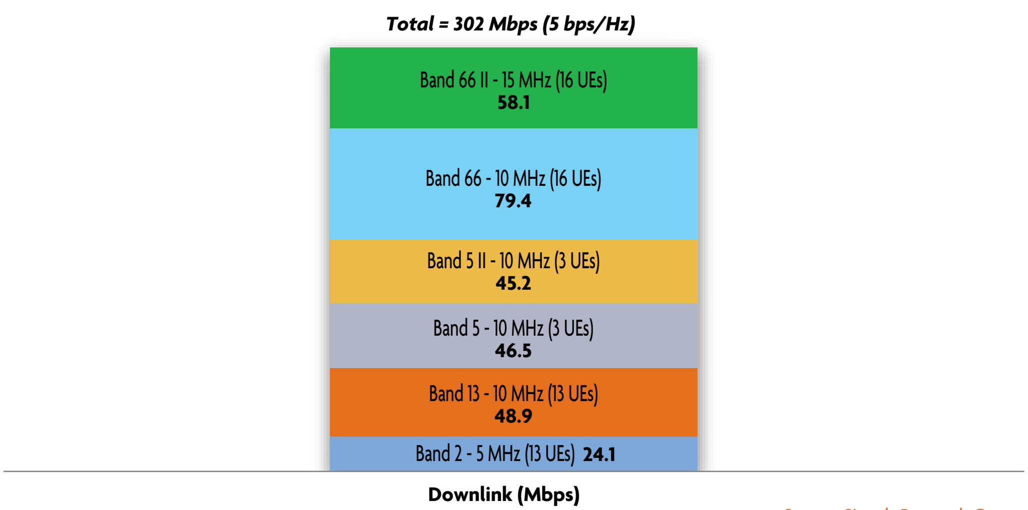
In this first section we present results which illustrate the total network capacity within the area we tested. These results are based on downlink and uplink testing with full buffer data transfers as well as the use of different SIM cards to lock the phones to LTE only or to allow the phones to use 5G NR mmWave. We also tested in mixed mode with some phones locked to LTE only and some phones allowed to use 5G NR.

3.1.1 LTE Total Capacity and Individual Data Speeds

The LTE total throughput was 302 Mbps.

Figure 3 shows the amount of data traffic on each LTE band when all sixteen smartphones had a full buffer downlink data transfer over LTE. For this test, all smartphones used 4-carrier carrier aggregation (4CCA). Since we didn't control the band selections, the smartphones selected different combinations of LTE bands (i.e., each smartphone used four LTE bands out of the six available LTE bands). Over the available bands, the LTE total throughput was 302 Mbps, equating to a measured spectral efficiency of 5 bps/Hz. The somewhat uneven distribution of smartphones across the available LTE bands, combined with some unallocated resource blocks explains the lower-than-expected spectral efficiency.

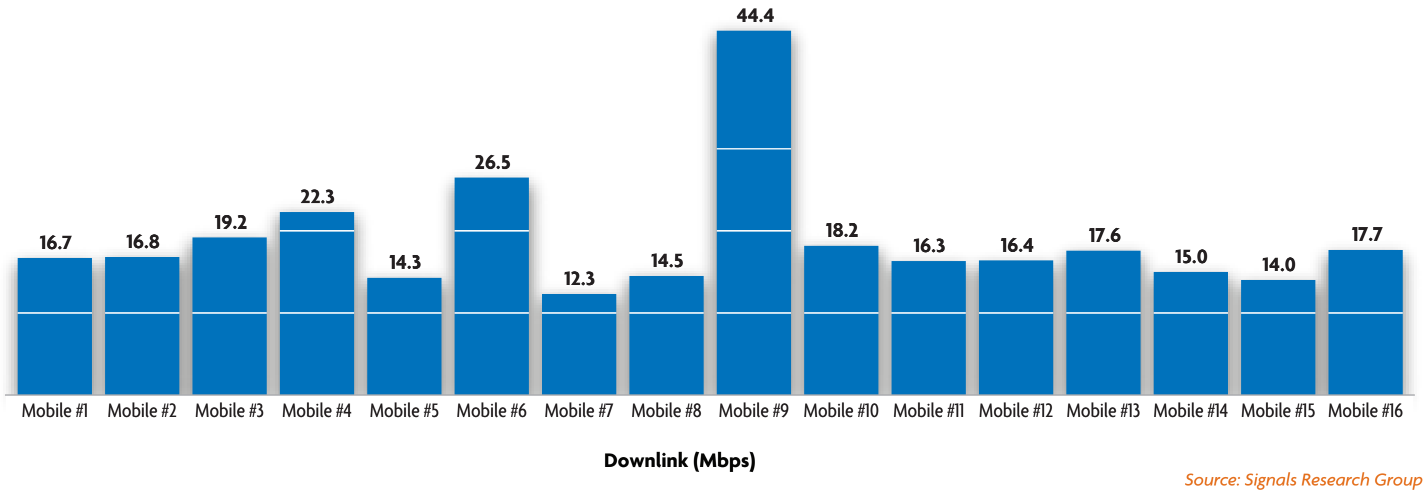
Figure 3. LTE Downlink Throughput per Smartphone



Source: Signals Research Group

Figure 4 shows the average LTE throughput for all sixteen smartphones. The result for Mobile #9 stands out because its throughput (44.4 Mbps) was much higher than its peers. This outcome stems from its use of both Band 5 channels. Both bands only had three smartphones and Mobile #9 was the only smartphone to use both channels, along with the two Band 66 channels.

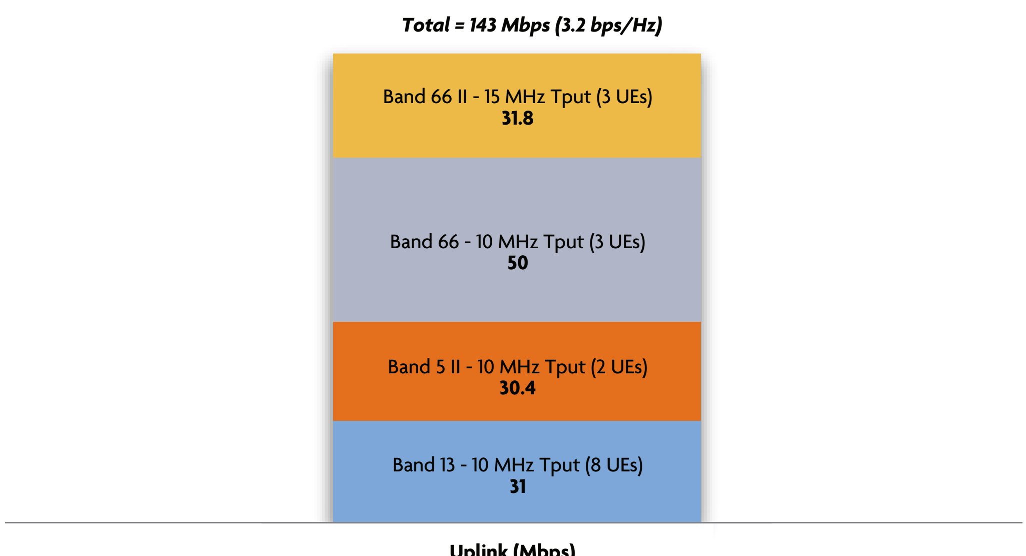
Figure 4. LTE Total Capacity and Spectral Efficiency - Downlink



Source: Signals Research Group

Switching to the uplink, Figure 5 shows the total uplink throughput was 143 Mbps with sixteen phones on LTE for a spectral efficiency of 2.6 bps/Hz. In this test none of the smartphones used Band 2 or one of the two Band 5 channels. We excluded these bands in our spectral efficiency calculation. We also note that when we did this testing the LTE network did not support uplink carrier aggregation and the use of this feature might have triggered the use of these bands for the secondary carrier. Since we did the testing in the Footprint Center, Verizon has introduced

Figure 5. LTE Total Capacity and Spectral Efficiency - Uplink

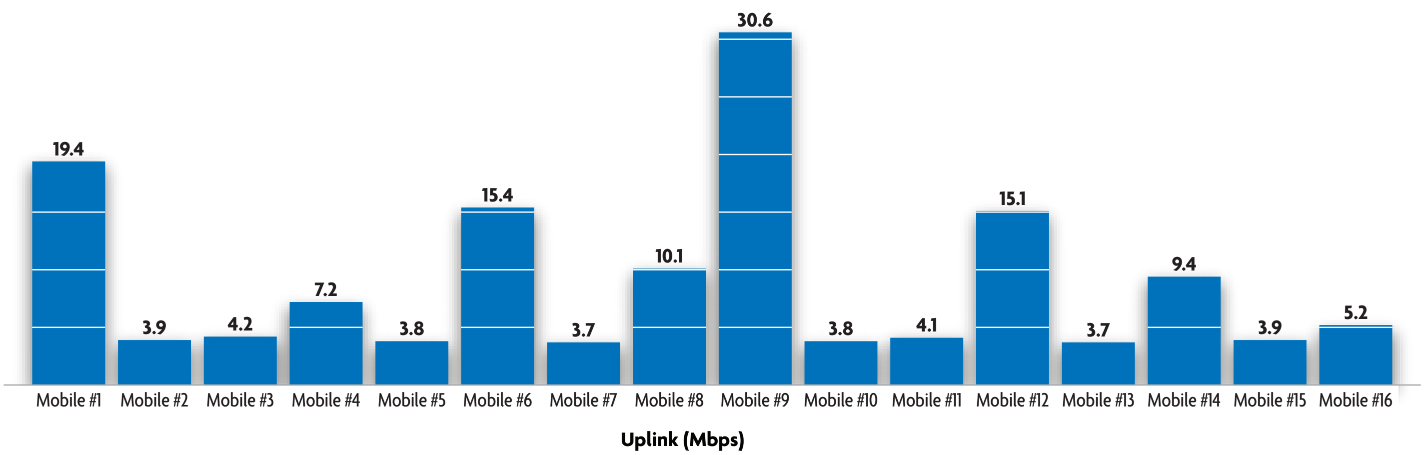


Source: Signals Research Group

uplink carrier aggregation with its LTE network. Like the downlink spectral efficiency, the uplink spectral efficiency was impacted by the uneven distribution of smartphones across the available LTE bands.

Figure 6 provides the average uplink data speed for each smartphone. Mobile #9 had much higher throughput than its peers, in part because it was using Band 66 (15 MHz channel) and because it received a disproportionate amount of network resources, compared with the two other smartphones that shared this radio channel.

Figure 6. LTE Uplink Throughput per Smartphone



Source: Signals Research Group

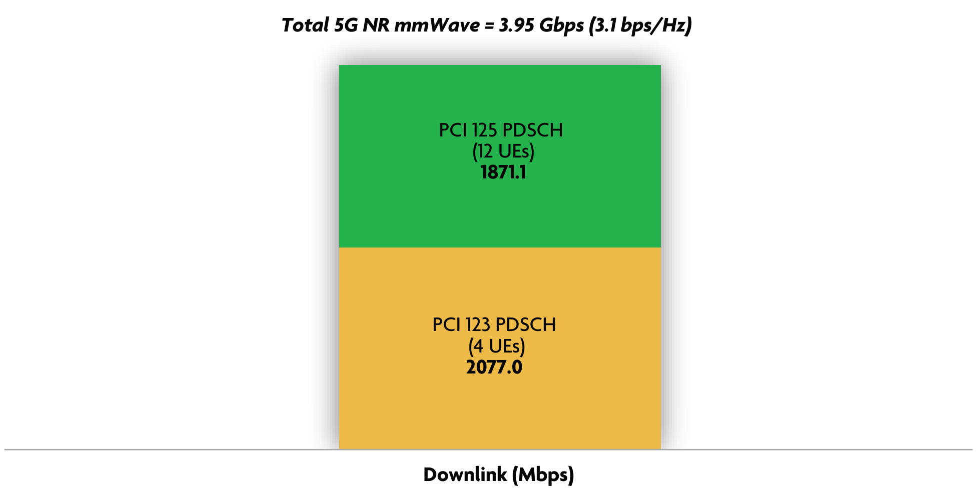
3.1.2 5G NR Total Capacity and Individual Data Speeds

The results in this sub section were obtained with the smartphones using SIM cards with a 5G NR subscriber profile. With the uplink tests, the smartphones used 5G NR mmWave and LTE, so we include the throughput contributions from both technologies.

With all sixteen smartphones supporting 5G NR, we observed a total 5G NR throughput of 3.95 Gbps, or roughly 13x the total LTE throughput. This result is based on the combined contributions from two different 5G NR mmWave radios. We point out each smartphone remained at the same location when testing LTE and when testing 5G NR mmWave, making it an apples-to-apples comparison with LTE. When calculating the spectral efficiency, as shown in Figure 7, we used an average throughput from the two 5G NR mmWave radios with each radio supporting 800 MHz of spectrum, of which 80% of the time was allocated to the downlink direction.

We observed a total 5G NR throughput of 3.95 Gbps, summed over two PCIs, or roughly 13x the total LTE throughput.

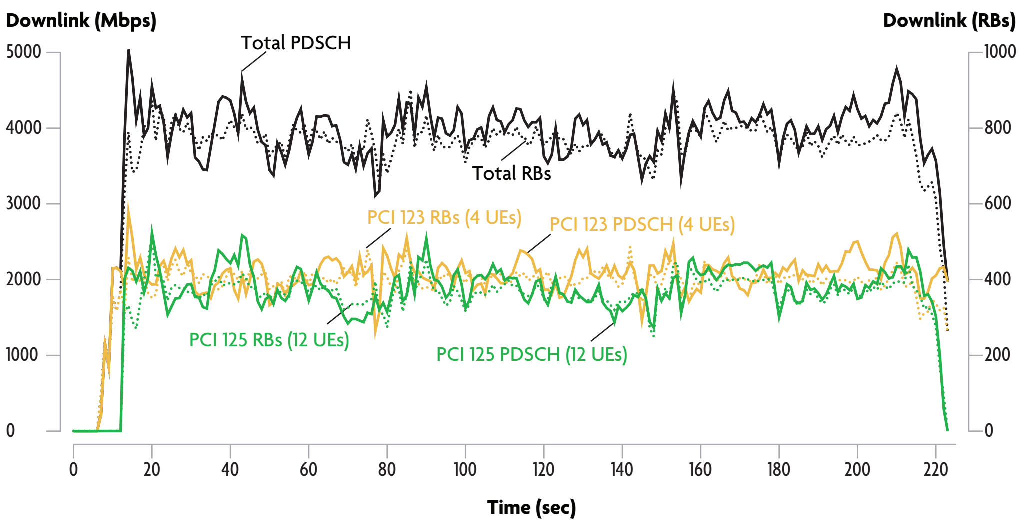
Figure 7. 5G NR Downlink Throughput and RB Allocations per PCI



Source: Signals Research Group

In Figure 8 we provide a time series plot of the total throughput and resource block (RB allocations) for the two 5G NR mmWave radios. The RB allocations are plotted along the secondary Y axis. As indicated in the figure, the RB allocations within each mmWave radio channel indicate not all RBs were allocated to the smartphones.

Figure 8. 5G NR Total Capacity and Spectral Efficiency

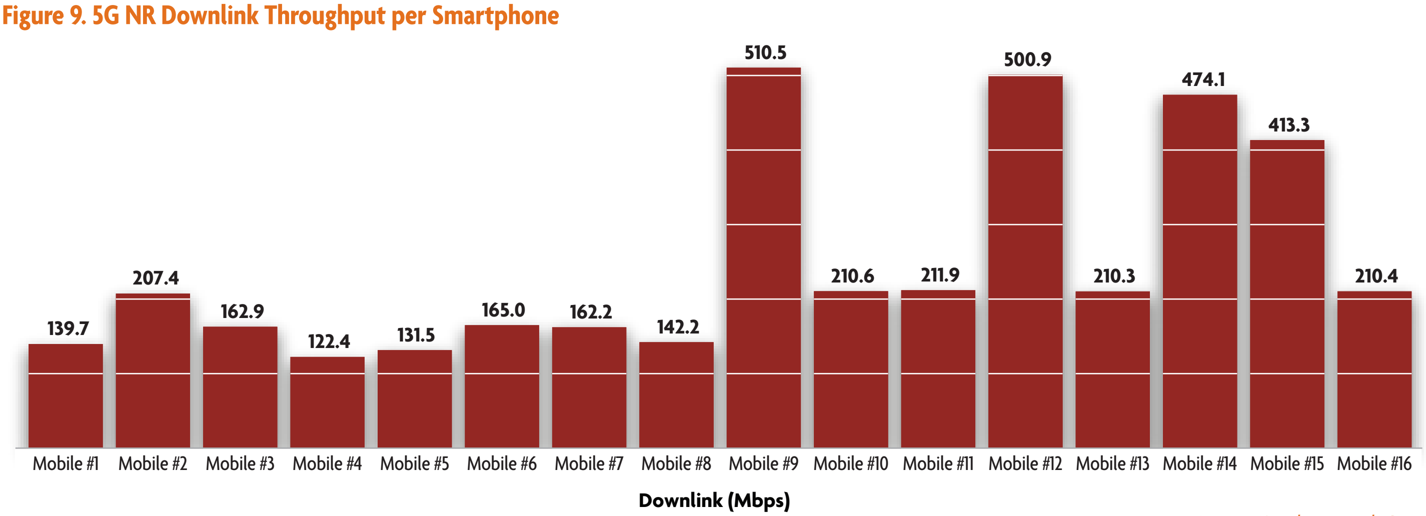


Source: Signals Research Group

Figure 9 shows the average throughput for each smartphone during the test. The results for four smartphones (#9, #12, #14 and #15) are noticeably higher than their peers because only these four smartphones shared the same 5G NR mmWave radio while the remaining twelve smartphones shared the other 5G NR mmWave radio. Compared with the LTE results, the smartphones' throughput was between 5.5x and 31.1x higher with 5G NR enabled. The performance gap between the two tests would have been even greater if the smartphones had leveraged PDCP combining with LTE.

Compared with the LTE results, the smartphones' throughput was between 5.5x and 31.1x higher with 5G NR enabled.

Figure 9. 5G NR Downlink Throughput per Smartphone

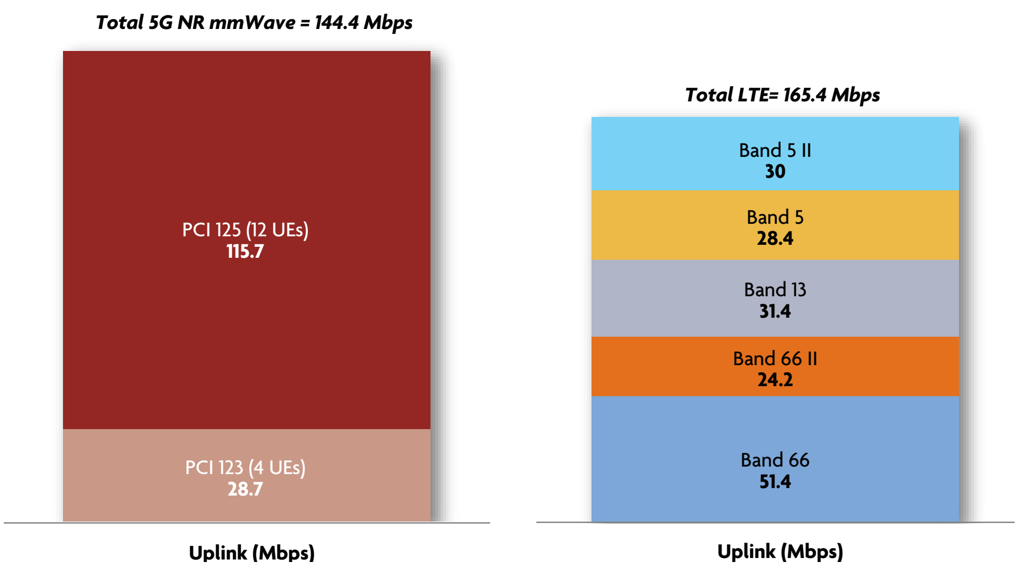


Source: Signals Research Group

Figure 10 provides the results for the uplink data tests. Since the smartphones leveraged PDCP combining with uplink data transfers, each smartphone had a 5G NR mmWave and an LTE component to its total throughput. At a high level, it is evident 5G NR mmWave roughly doubled the total throughput in the uplink direction. The gain would have been much higher (theoretically up to a 2x gain in the 5G NR throughput) if all the smartphones had leveraged uplink-CA on 5G NR mmWave instead of only using a single 100 MHz channel. Figure 11 indicates Mobile #13 used uplink-CA (2x100 MHz) for the entire test and that Mobile #10 used uplink-CA for a small portion of the test. As previously noted, although we observed the smartphones occasionally using uplink-CA with 5G NR mmWave, the usage was very infrequent due to network thresholds which triggered its use. We also note the uplink throughput for PCI 123 was surprisingly low relative to our expectations. The performance of PCI 125, we believe, is more typical of 5G NR mmWave performance for a single 100 MHz carrier used for uplink data transfers. With 2x100 MHz available for uplink data transfers the uplink throughput would have been nearly double what is shown in the figure.

5G NR mmWave roughly doubled the total bandwidth available for the uplink – the total throughput would have been much higher if the smartphones leveraged uplink-CA.

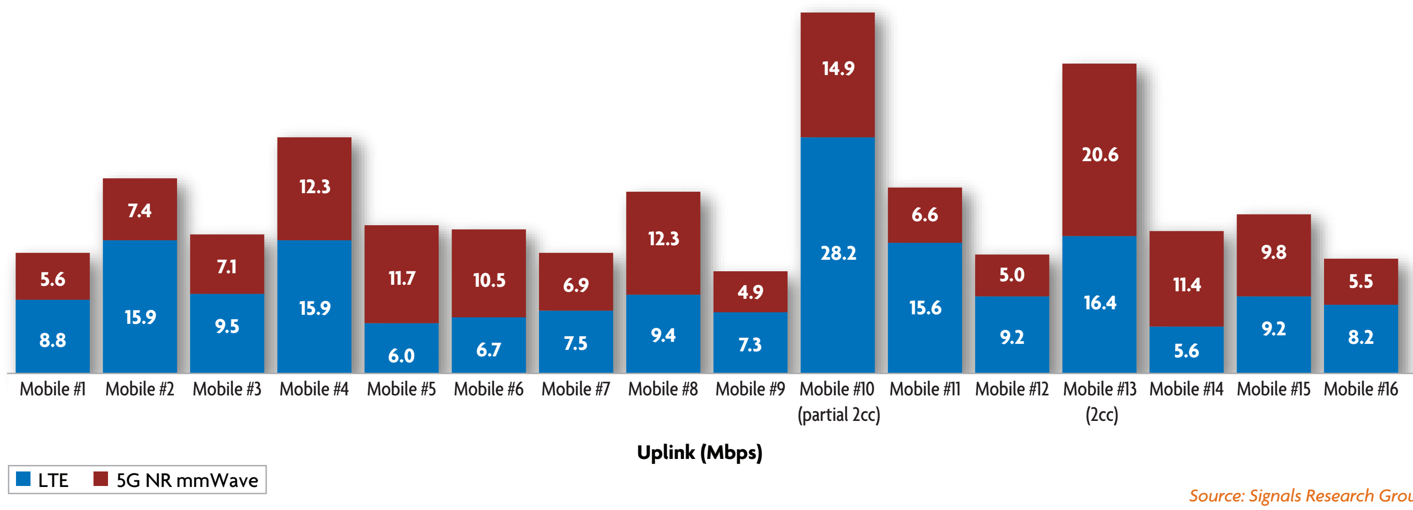
Figure 10. 5G NR and LTE Uplink Throughput



Source: Signals Research Group

Figure 11 shows the total uplink throughput for each smartphone, including the contribution from 5G NR mmWave and from LTE. Differences in the uplink throughput between the smartphones was largely based on the LTE anchor band the smartphones were using.

Figure 11. 5G NR and LTE Uplink Throughput per Smartphone



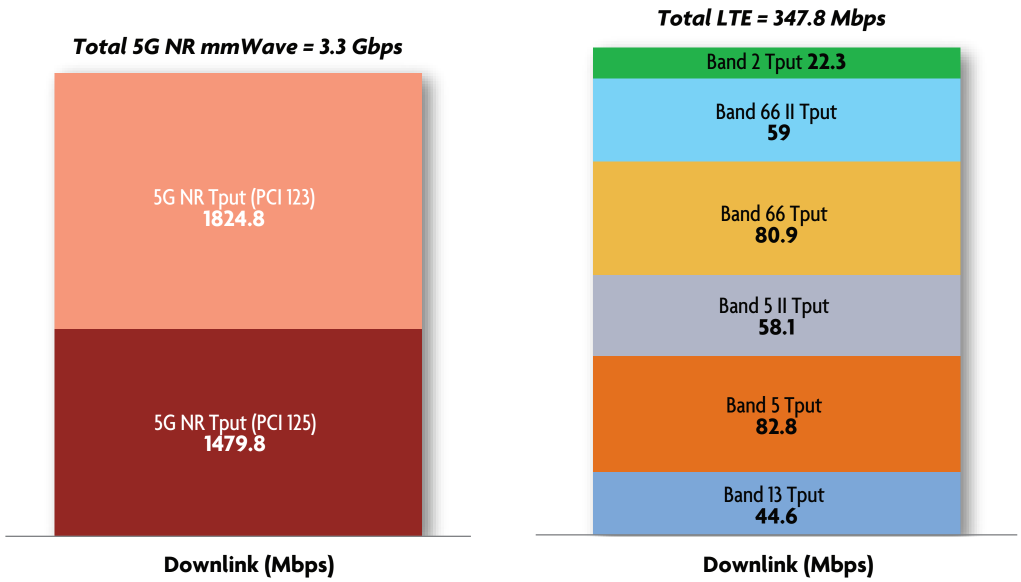
Source: Signals Research Group

We also did a few bandwidth tests which involved a mix of smartphones using 5G NR mmWave and LTE only. The remaining figures in this section stem from that testing. Figure 12 shows the total downlink throughput over 5G NR mmWave for the four smartphones with 5G NR service provisioning and the LTE throughput for the remaining twelve smartphones which were provisioned for LTE only. The total 5G NR mmWave throughput was 9.5x higher than the LTE throughput.

During this test, one of the 5G NR mmWave smartphones switched from using PCI 125 to PCI 123. The information shown in Figure 12 stems from that portion of the test when the smartphone was using PCI 125. The average throughput for each smartphone shown in Figure 13 is based on the full test length, including times when the one smartphone was using PCI 125 and when it was using PCI 123. We believe this approach more accurately reflects the capabilities of the network even though the 5G NR results shown in each figure are different. The 5G NR mmWave smartphones had an average throughput (539.9 Mbps) that was 18x higher than the average LTE throughput (29.8 Mbps) for the remaining twelve smartphones that were limited to LTE. The use of PDCP combining would have given the 5G NR mmWave smartphones an even greater performance advantage.

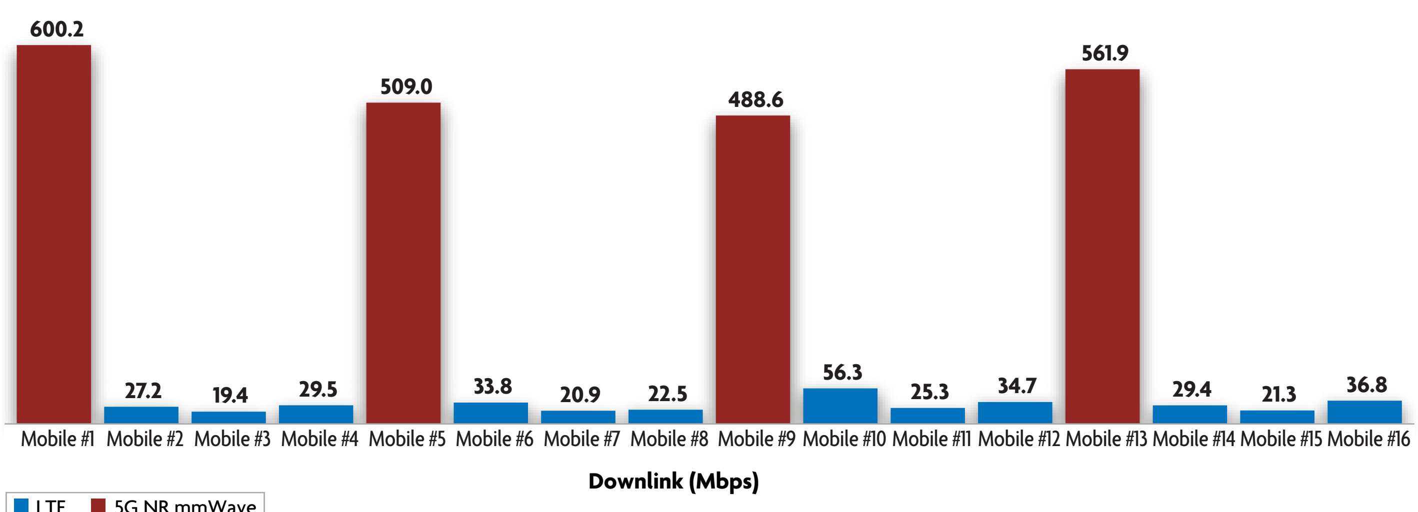
The 5G NR mmWave smartphones had an average throughput that was 18x higher than the average LTE throughput for the LTE only smartphones.

Figure 12. 5G NR and LTE Downlink Throughput – 4 Smartphones on 5G NR



Source: Signals Research Group

Figure 13. 5G NR and LTE Downlink Throughput per Smartphone – 4 Smartphones on 5G NR

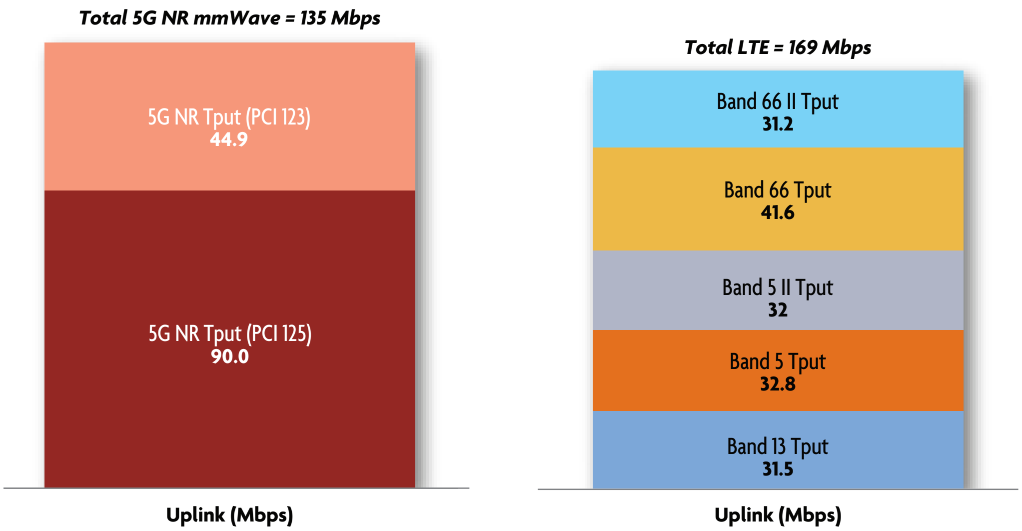


Source: Signals Research Group

Figure 16 provides the total uplink throughput for the four smartphones using 5G NR mmWave and the total LTE throughput for the remaining twelve smartphones that were provisioned for LTE only as well as the four 5G NR mmWave smartphones that also used the LTE anchor band for uplink data transfers. In this test, Mobile #9 used uplink-CA on 5G NR mmWave so its throughput was much higher than the other three smartphones which used a single 100 MHz 5G NR channel for uplink data transfers.

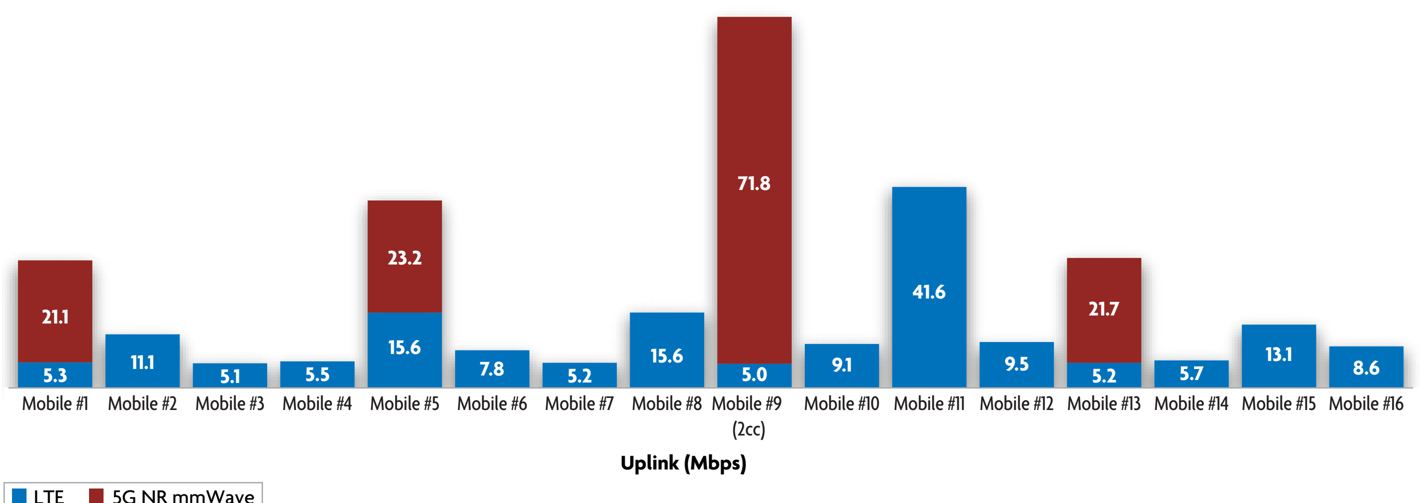
5G NR mmWave roughly doubled the total uplink throughput available in the venue – the use of uplink-CA would have resulted in an even higher performance gain.

Figure 14. 5G NR and LTE Uplink Throughput – 4 Smartphones on 5G NR



Source: Signals Research Group

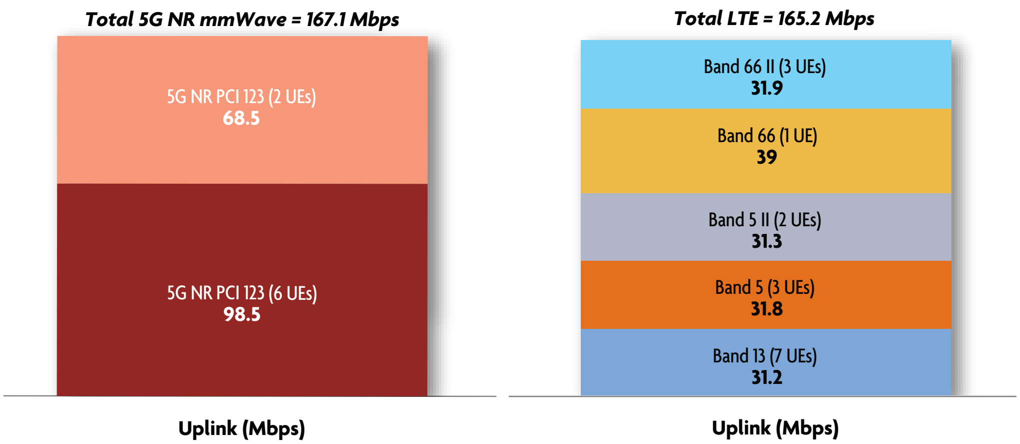
Figure 15. 5G NR and LTE Uplink Throughput per Smartphone – 4 Smartphones on 5G NR



Source: Signals Research Group

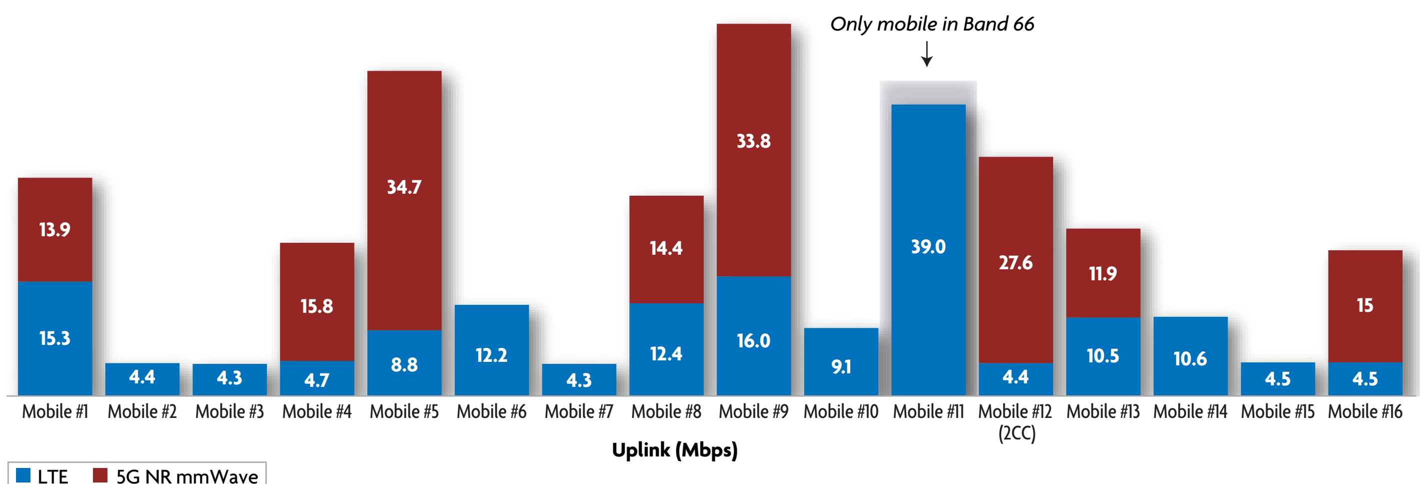
We then increased the number of smartphones supporting 5G NR mmWave to eight smartphones. Figure 16 provides the total uplink throughput for the smartphones using 5G NR mmWave and the total LTE throughput for the remaining eight smartphones that were LTE only as well as the eight 5G NR mmWave smartphones that also used the LTE anchor band for uplink data transfers. The total throughput over 5G NR mmWave and over LTE was approximately equivalent at 165 Mbps each. On a per device basis, those smartphones with 5G NR mmWave enabled had nearly 3x higher throughput than the smartphones that only supported LTE. With the four device scenario (Figure 15), the relative gain was 3.7x.

Figure 16. 5G NR and LTE Uplink Throughput – 8 Smartphones on 5G NR



Source: Signals Research Group

Figure 17. 5G NR and LTE Uplink Throughput per Smartphone – 8 Smartphones on 5G NR



Source: Signals Research Group

On average, the smartphones which used 5G NR mmWave and LTE for the uplink data transfer had a throughput that was 2.5x higher than those smartphones which only used LTE. Mobile #11 had remarkably high throughput for a smartphone that was only using LTE. Upon further analysis we discovered this smartphone was the only smartphone using Band 66 (15 MHz carrier).

On average, the smartphones which used 5G NR mmWave and LTE for the uplink data transfer had a throughput that was 2.5x higher than those smartphones which only used LTE.

3.2 Video Broadcasting Radio Network Requirements and the Impact of Network Loading – Uplink Specific

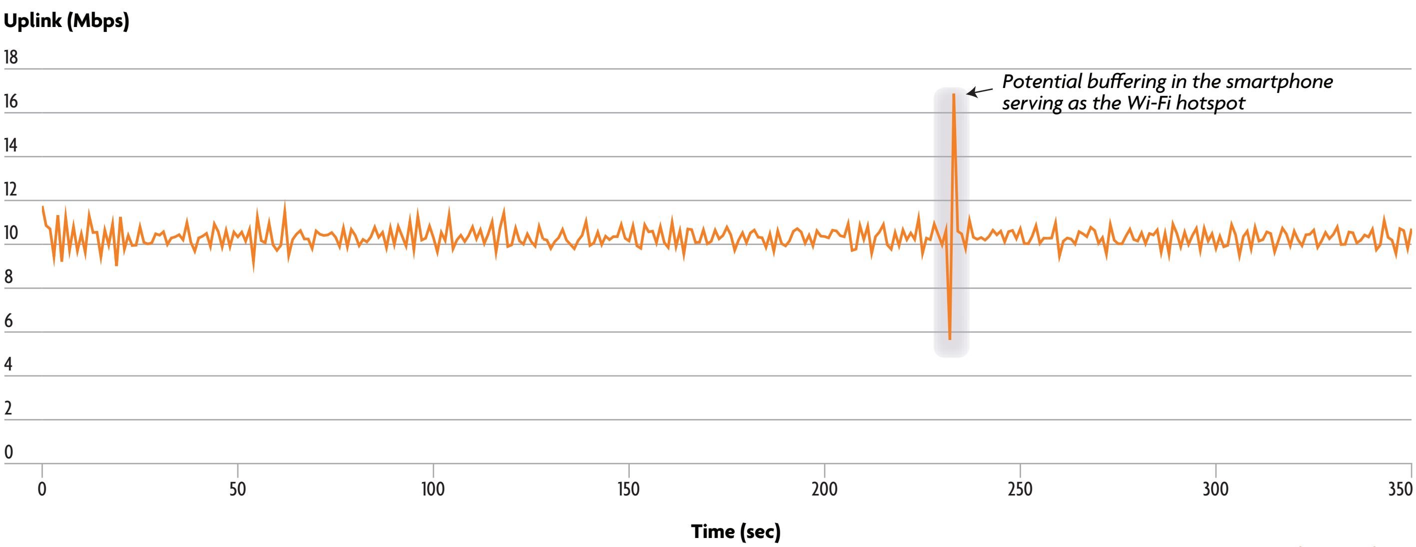
In addition to testing overall network capacity and individual throughput, we also quantified the incremental benefits of 5G NR mmWave on the user experience, specifically video. We included two primary scenarios: someone watching a video on the smartphone and someone live streaming their experience while at the venue. The former stresses the downlink direction and the latter stresses the uplink direction.

In this section, we show the results from our tests of live streaming. We used YouTube Live as the social media platform for these tests. Since our YouTube Live account didn't allow us to stream from a smartphone, we used a notebook computer connected via Wi-Fi (802.11ac) to a Galaxy S20 smartphone that served as a Wi-Fi hot spot with backhaul provided over the cellular network, either LTE or 5G NR mmWave.

3.2.1 Network Resource Requirements

In our tests, we looked at the bandwidth requirements for the streaming content and how network loading impacted the bandwidth usage during a streaming session. Figure 18 provides a time series plot of the uplink physical layer throughput while streaming live to YouTube. We did this YouTube Live session over LTE (unloaded). As shown in the figure, the uplink throughput remained relatively constant during the session, or between 10-12 Mbps. There was one blip in the throughput that we have highlighted in the figure. It isn't clear to us what happened, but it was possibly caused by the Wi-Fi hotspot storing data in its buffer and then bursting out the data onto the LTE network.

Figure 18. YouTube HD Video Broadcast Radio Network Resource Requirements



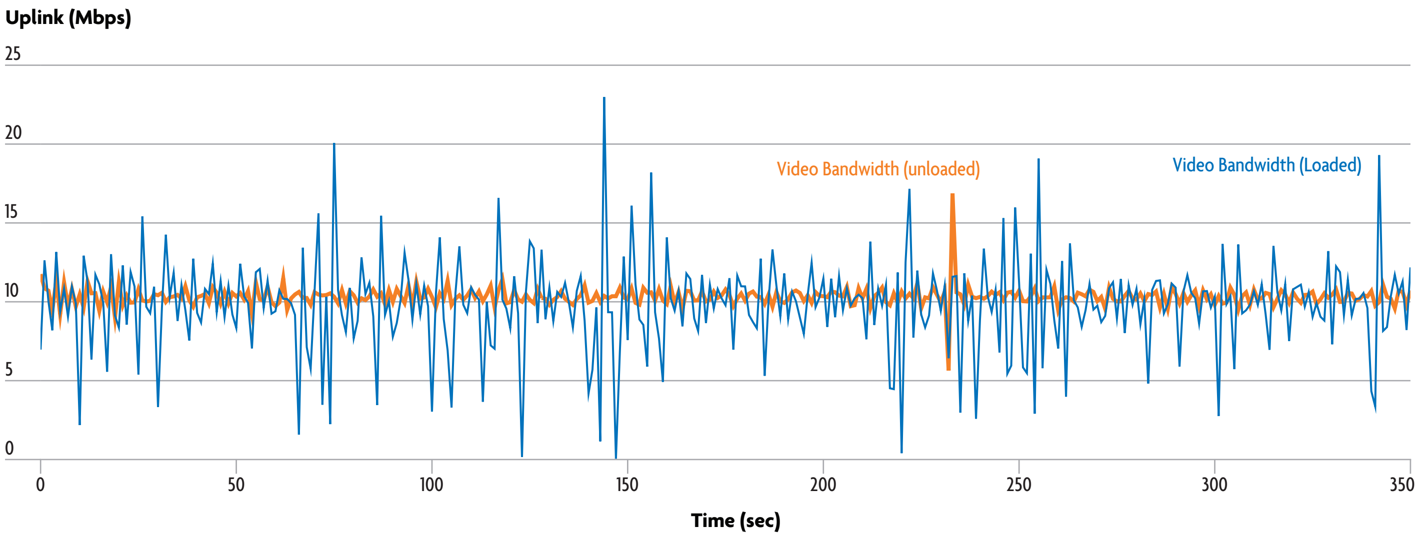
Source: Signals Research Group

After finishing this test in an unloaded network, we repeated the test but this time we introduced 16 additional smartphones doing full buffer uplink data transfers over LTE in the same serving cell used for the video. Like the smartphone we used for the Wi-Fi hot spot, these smartphones were not locked to any particular LTE band, so the network spread the uplink data traffic over all LTE carriers. With additional network loading, the uplink traffic associated with the YouTube Live video stream was more erratic, as shown in Figure 19. In this figure, we also included the YouTube Live throughput with an unloaded network to show the contrast between the two scenarios.

With additional network loading, the uplink traffic associated with the YouTube Live video stream was more erratic.

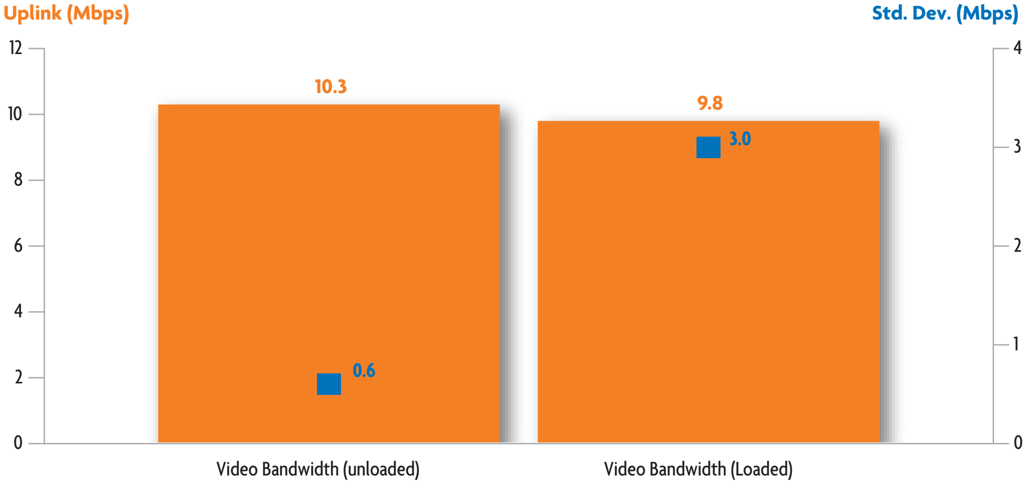
Figure 20 provides the average throughput and the standard deviation of the throughput for the loaded and unloaded scenarios. With loading, the average throughput was slightly lower (9.8 Mbps versus 10.2 Mbps), but most importantly there was a dramatic increase in the standard deviation of the throughput, or 3.0 Mbps versus 0.6 Mbps. The latter is perhaps a better indicator of the impact of network loading. Obviously, if a smartphone transmitting a video has 0 Mbps of uplink data traffic then the smartphone isn't sending any video traffic and freezes are likely to occur. Interestingly, in this test our analysis of the video performance indicated there were only modest problems with the video performance, although we were right at the cusp of impacting the user experience even with the limited number of smartphones we had in our possession.

Figure 19. YouTube HD Live Video Broadcast Radio Network Resource Usage with Loading Time Series



Source: Signals Research Group

Figure 20. YouTube HD Live Video Broadcast Radio Network Resource Usage with Loading

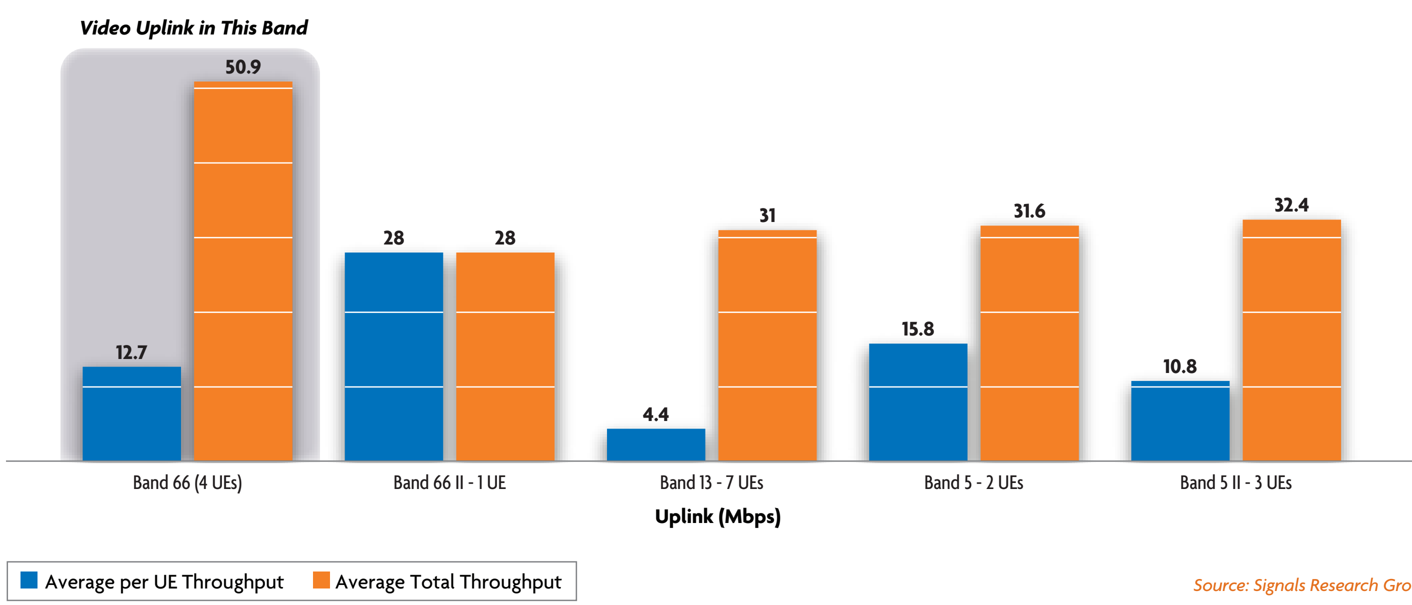


Source: Signals Research Group

As indicated in a previous paragraph, for this test we allowed all the smartphones, including the smartphone we used for the YouTube Live video transmission, to be assigned to any available LTE band, meaning the network distributed the traffic across all available LTE radio channels. Figure 21 shows the distribution of uplink traffic across the available LTE channels, the number of smartphones (User Equipment or UE) on each band, and the average throughput of the smartphones on each available LTE band. The information in the figure indicates the smartphone carrying the YouTube Live video traffic used LTE Band 66 with a 15 MHz channel bandwidth, or the widest available LTE channel in the venue. With only four smartphones using this band, the average uplink throughput was 12.7 Mbps, or just enough to support the video broadcast. If the smartphone had used Band 13 or Band 5 II then there would have been more congestion in the radio channel and we would have observed various video impairments, which

The distribution of smartphones and their associated data traffic across the available LTE bands is not always uniform.

Figure 21. LTE Total Bandwidth and Average Smartphone Usage per Radio Channel



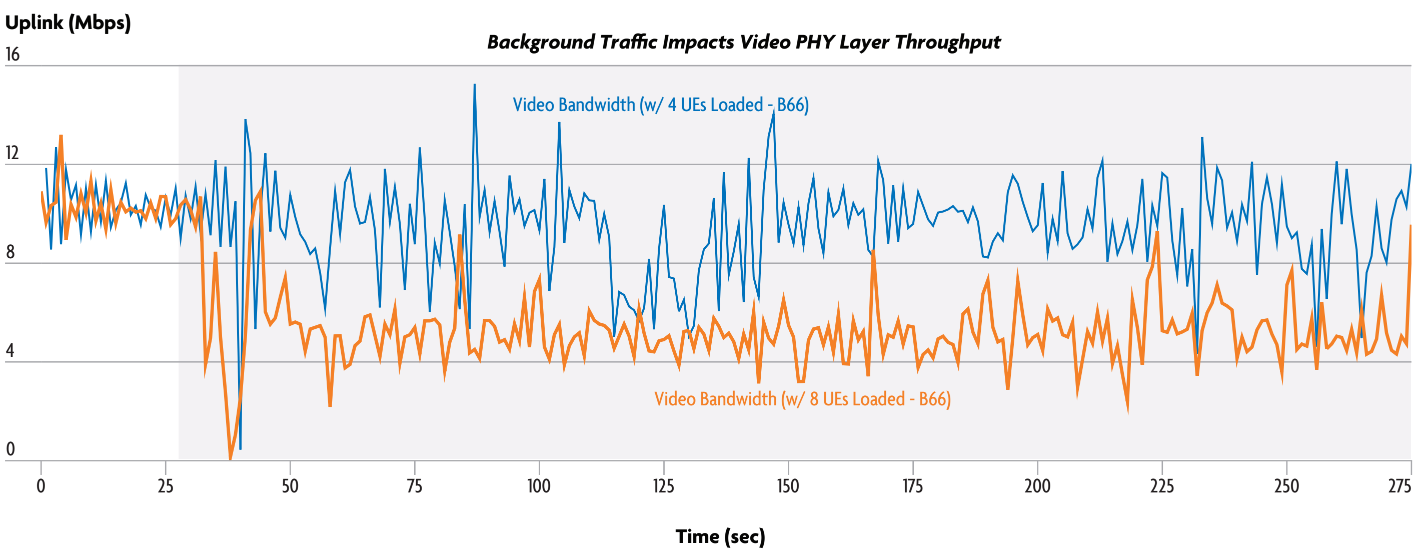
Source: Signals Research Group

would have impacted the user experience. Likewise, if one of the other smartphones, such as one of the 7 smartphones using Band 13, had been assigned LTE Band 66 then we would have also observed more congestion in the results. Conversely, if the network had assigned the smartphone carrying the YouTube video traffic to the other Band 66 channel, then there would have been less congestion than what we observed in our test results.

As a sensitivity study, we locked multiple smartphones to the Band 66 channel with 10 MHz channel bandwidth to determine the impact on the physical layer throughput for the smartphone supporting the YouTube Live video session. As shown in Figure 22, which only shows the uplink throughput for the smartphone with the YouTube Live video session, there was an obvious impact when 4 additional smartphones started using the same LTE radio channel and an even bigger impact with 8 additional smartphones using the same LTE radio channel with a 10 MHz channel bandwidth. With only 4 additional smartphones doing full buffer uplink data transfers, there would likely have been some impact to the user experience since the throughput frequently dropped below the 10-12 Mbps throughput that we determined the application required. And clearly with 8 additional smartphones there would have been a very detrimental impact to the user experience since the average throughput was frequently about half the required throughput for the uplink video transfer. In the next section we show how network congestion actually impacted the user experience in these tests, based on various video metrics that we analyzed.

There was an obvious impact on the YouTube Live video transfer with only 4 additional smartphones using the same LTE radio channel to do full buffer uplink data transfers.

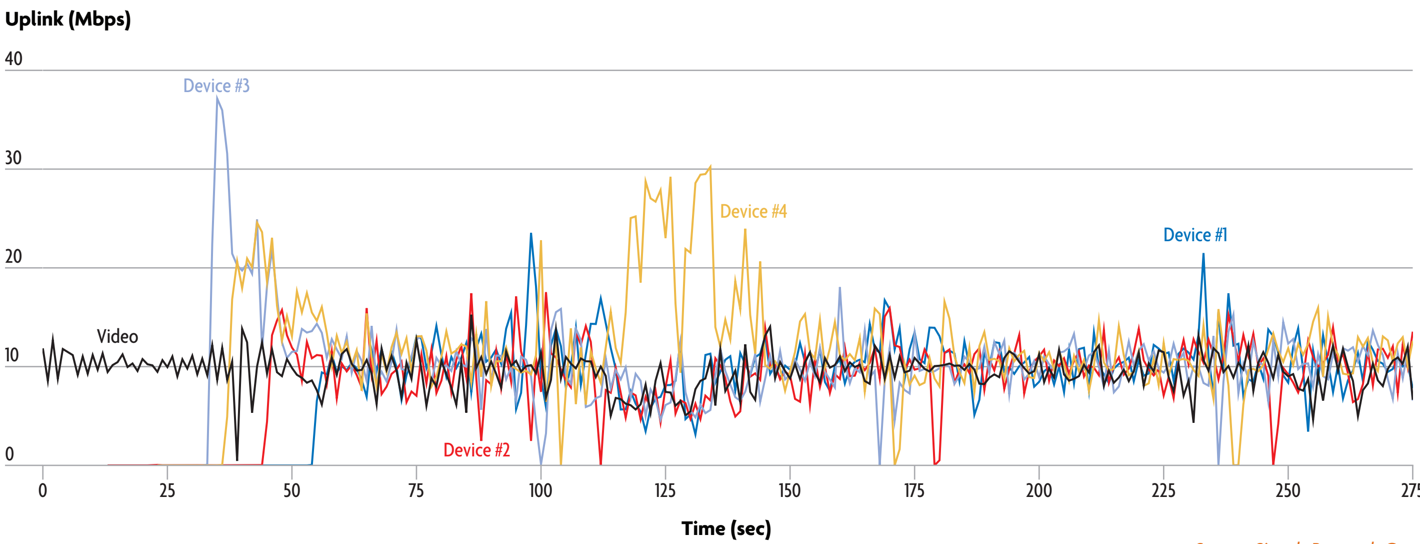
Figure 22. YouTube Video Broadcast Radio Network Usage with Loading in Band 66



Source: Signals Research Group

Figure 23 provides a time series plot of the physical layer throughput for four smartphones sharing the same LTE channel (Band 66), along with the smartphone used for the YouTube Live video session. The periodic drops in the throughput to 0 Mbps for the four additional smartphones occurred when the smartphones had finished the data transfer test session. For these tests, we used a two-minute data transfer test, which ran continuously during each test scenario. At the start of this session, the throughput for the smartphone with the YouTube Live session was relatively constant, but once the four additional smartphones started using the same radio channel, the smartphone's throughput was more variable with frequent drops below the target rate of 10-12 Mbps. The times when the smartphone's throughput fell below this target rate were relatively short, so there wasn't a measurable impact on the user experience.

Figure 23. LTE Throughput per Smartphone in LTE Band 66



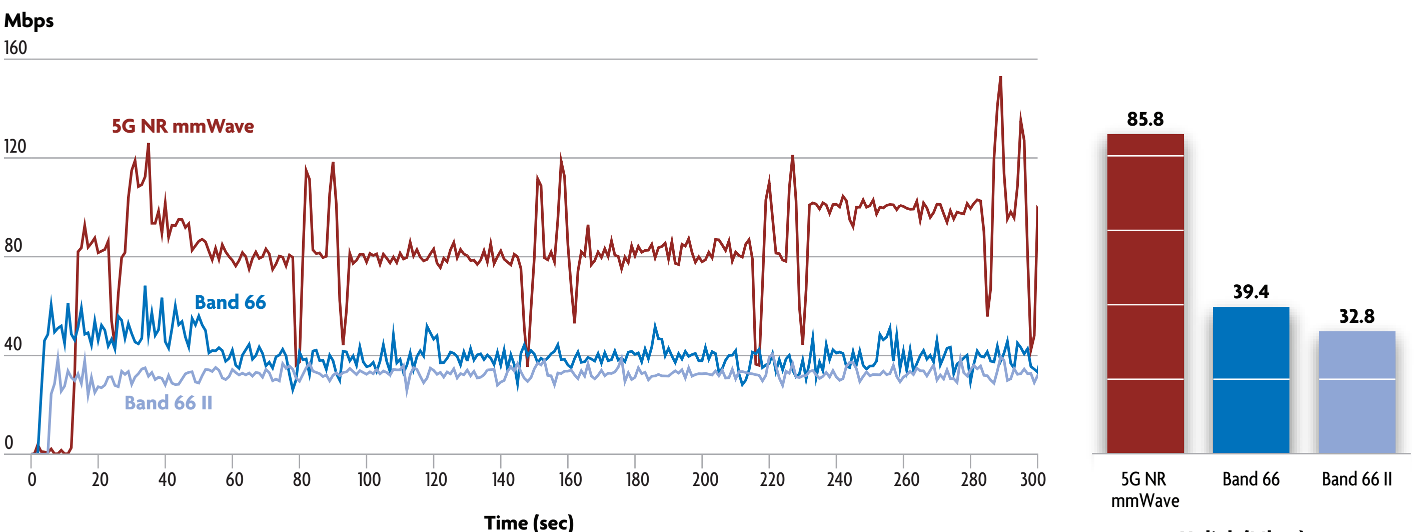
Source: Signals Research Group

After completing various video tests with the smartphones only supporting LTE, we enabled 5G NR mmWave on some of the smartphones, including the smartphone we were using for the YouTube Live video session. For one test, we had two smartphones doing full buffer uplink data transfers over 5G NR mmWave and an additional fourteen smartphones doing full buffer uplink data transfers over the two LTE Band 66 channels. The smartphone with the YouTube Live session was also using 5G NR mmWave for the uplink streaming of the video.

Figure 24 provides the average uplink throughput for the sixteen smartphones (14 smartphones LTE only and 2 smartphones with 5G NR mmWave enabled), as well as the total throughput on the two LTE bands and 5G NR mmWave. In this test the two 5G NR-enabled smartphones only used a single 100 MHz channel for the uplink data traffic so the observed throughput was approximately half the expected throughput with the full use of two 100 MHz channels – a doubling of throughput is possible, depending on the amount of available transmit power the smartphone has available. The total throughput shown in the figure does not include the contribution from the smartphone supporting the YouTube Live session. One obvious conclusion from these results is that there was more than ample 5G NR mmWave capacity to support the video session while it is equally evident the LTE capacity was far from sufficient to support the uplink video traffic. We provide video results for this test in the next section.

There was more than ample 5G NR mmWave capacity to support the video session while it is equally evident the LTE capacity was far from sufficient to support the uplink video traffic.

Figure 24. 5G NR and LTE Band 66 Uplink Throughput per Smartphone Background Traffic



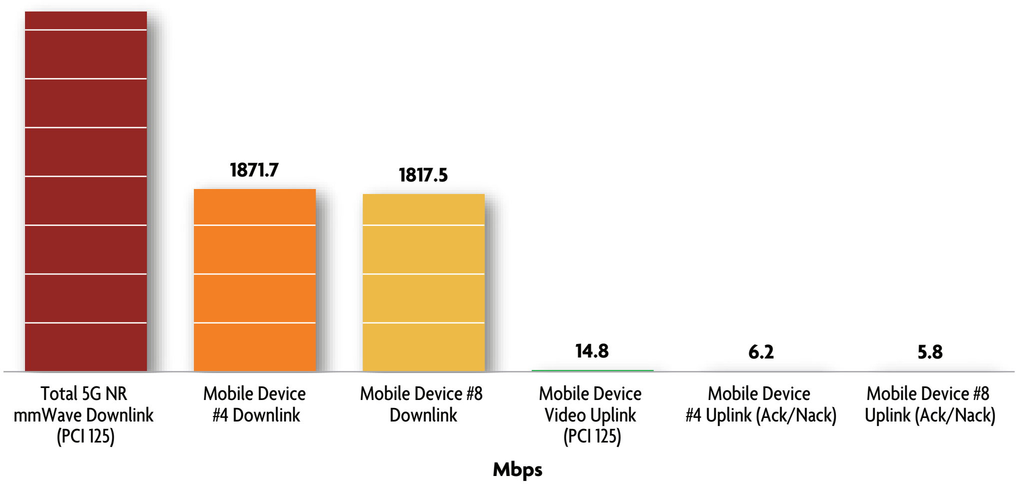
Source: Signals Research Group

Mobile network traffic is predominantly in the downlink direction and 5G NR mmWave is typically associated with providing massive amounts of downlink capacity. Since we have also demonstrated the benefits of 5G NR mmWave on uplink capacity in this paper, we are including results from a test scenario that combines the benefits of 5G NR mmWave on both downlink and uplink capacity. For this scenario, we used three smartphones, all sharing the same 5G NR mmWave radio (PCI 125). We started a full buffer downlink data transfer on two smartphones while the third smartphone supported the YouTube Live video session.

The same 5G NR mmWave site supported nearly 3.7 Gbps of downlink data traffic while simultaneously supporting the uplink YouTube Live session.

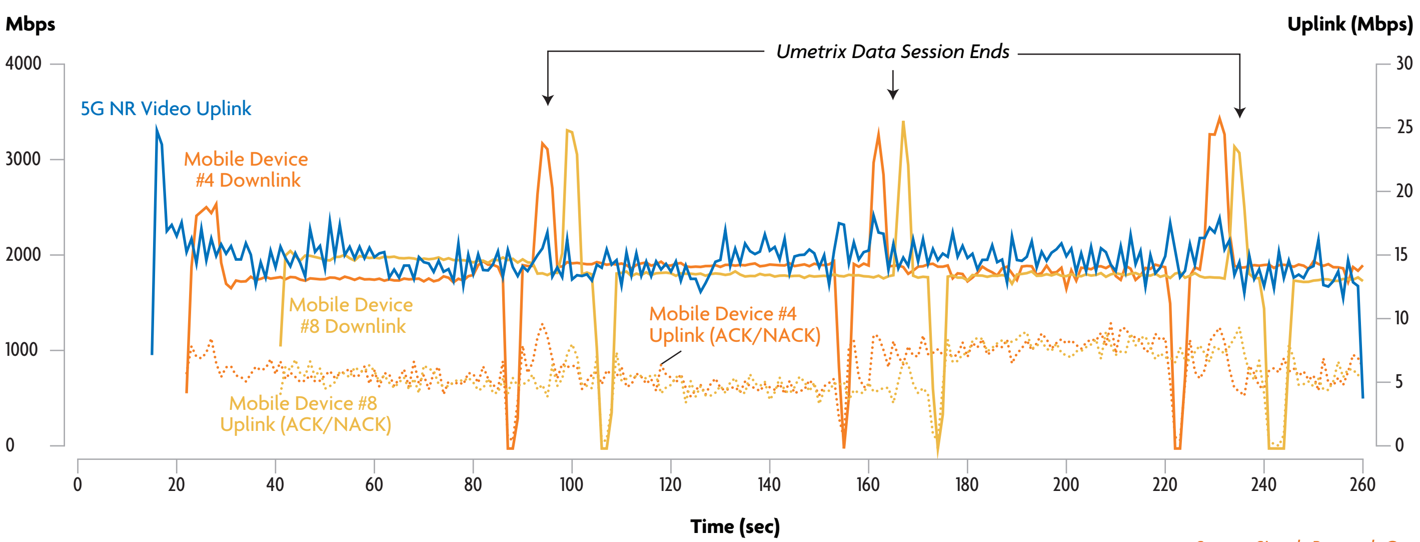
As shown in Figure 25, the same 5G NR mmWave site supported nearly 3.7 Gbps of downlink data traffic while simultaneously supporting the uplink YouTube Live session and the ACK/NACKs from the two smartphones with the full buffer data sessions. In comparison to the downlink data traffic, the uplink data traffic was trivial, but more than sufficient to provide a good user experience (video metrics are included in the next section). Lastly, Figure 26 provides a time series plot of the downlink and uplink throughput for the three smartphones. Due to the large disparity in the throughput between the downlink and uplink directions, we have plotted the downlink throughput along the primary Y axis and the uplink throughput along the secondary Y axis.

Figure 25. 5G NR Downlink and Uplink Throughput plus 5G NR Video Broadcast Throughput



Source: Signals Research Group

Figure 26. 5G NR Downlink and Uplink Throughput plus 5G NR Video Broadcast Throughput Time Series



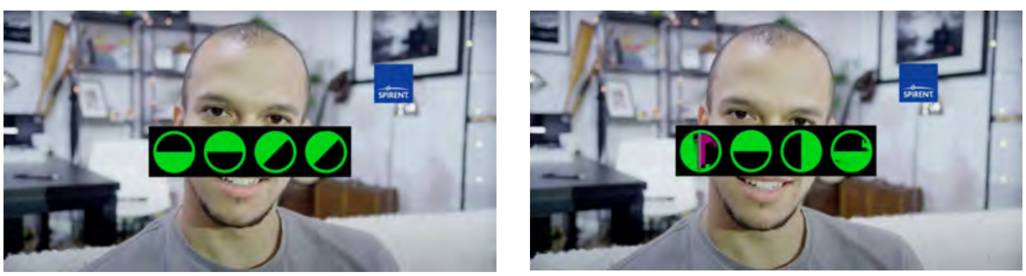
Source: Signals Research Group

3.2.2 Video Performance Results

There are two ways to evaluate and show video performance results. One approach is to provide relevant metrics, such as the observed frame rate, freezes and frame impairments, etc. The second approach is to provide still images of the videos to demonstrate the differences in the video experience, the impact of network loading, and the benefits of 5G NR mmWave. We elected to incorporate both approaches in this paper.

For the uplink video tests, we used gross error detection (GED) to analyze video performance. Specially, we used a test video with inserted reference markers to evaluate video performance on a frame-by-frame basis. This approach allows us to observe the frame rate of the video and to identify video freezes or impairments. Figure 27 illustrates an example of video impairments. The figure shows two still images from the YouTube Live video that we streamed to the YouTube server. The image on the left – the Good Image – shows the four reference circles that constantly spin when the video is playing. Deviations to the rate of each spinning circle from their expected spin rate indicate changes in the observed frame rate. A frozen circle(s), as one might expect, identifies a video freeze. The image on the right – the Bad image – shows an example of a video impairment.

Figure 27. Good Video versus Bad Video



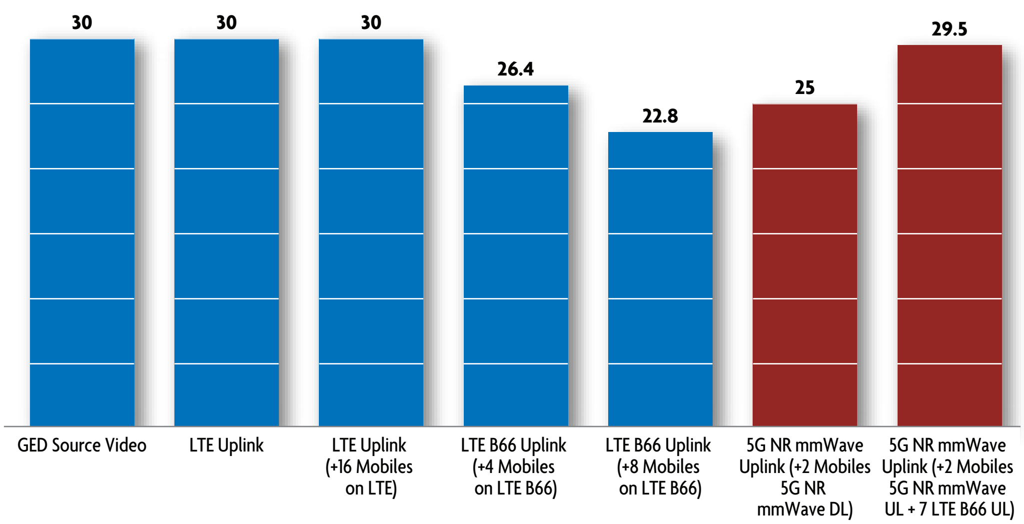
Good **Bad**

Source: Signals Research Group

Figure 28 provides the average frame rate for several video tests that we conducted, and which we analyzed in the previous section. The GED Source Video result (30 fps) stems from a test in which we played the video on the smartphone without any interaction with YouTube or the cellular network. We used this test as a benchmark for the additional tests. The LTE Uplink result (30 fps) involved a test in which we streamed the test video to the YouTube Live server without any additional traffic on the network. We showed the physical layer throughput from this test in Figure 18. The third bar from the left (LTE Uplink (+16 Mobiles on LTE) shows the observed frame rate matched the source video at 30 fps. As we indicated in the previous section when discussing Figure 19 through Figure 21, the background traffic was just low enough to avoid impacting the user experience. This statement is supported by the observed frame rate remaining at 30 fps with network loading. There is, however, a direct correlation between the LTE physical layer throughput and the video quality. If the physical layer throughput is too low to support the video playback then there will be freezes and/or a reduced video frame rate. When we spread the background traffic across all bands, we showed the increased variability in the physical layer throughput for the smartphone streaming the video content. However, with the limited number of smartphones we used in this study, we weren't able to generate enough network loading to impact the video.

The trend, however, is apparent, and when we restricted the smartphones to Band 66, we are able to show an impact on the video user experience. Similarly, the trend in the data indicates that with more background traffic or if the distribution of the traffic across the LTE bands was slightly different (e.g., the smartphone playing the video had used Band 13 or Band 5 instead of Band 66) then the user experience would have been detrimentally impacted. This statement is supported by the average throughput observed in those bands, which was much lower than required to support the uplink video stream.

Figure 28. Observed Frames Per Second

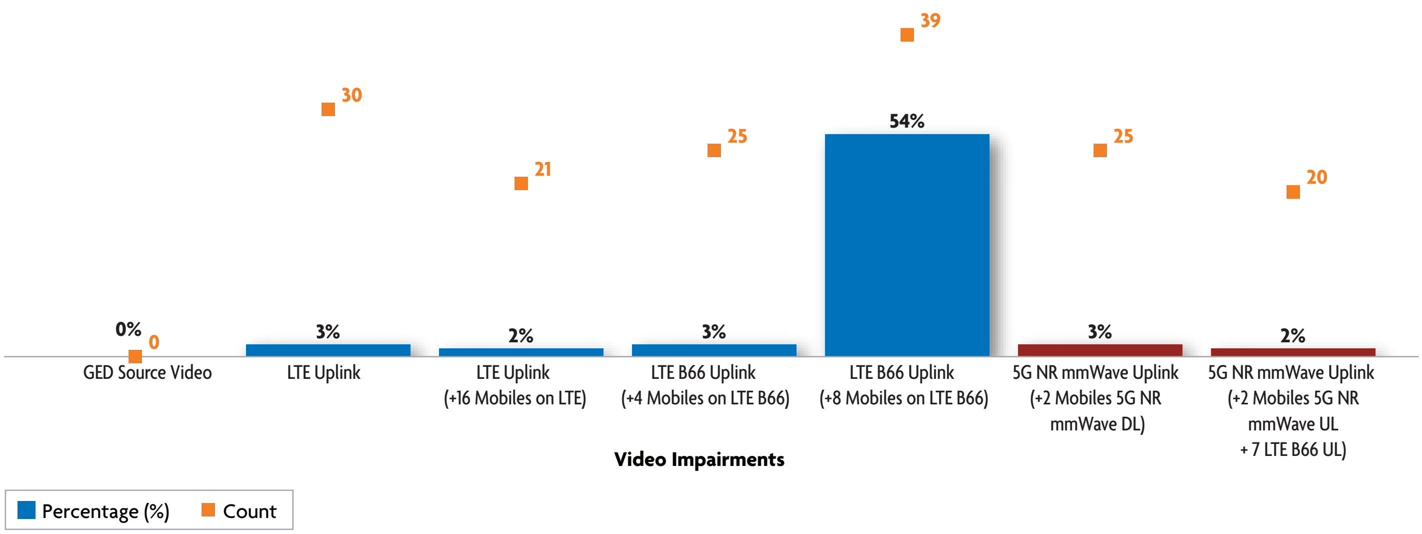


Source: Signals Research Group

When we forced the background traffic to share the same channel as the uplink video traffic then there was a noticeable drop in the observed frame rate, as indicated in the next two bars. With four smartphones generating uplink data traffic on Band 66 the observed frame rate was 26.5 fps, dropping to 22.8 fps with eight smartphones sharing the channel with the smartphone streaming the video to YouTube Live. We shared the physical layer throughput for these two scenarios in Figure 22. The last two bars show the average frame rate with the two 5G NR mmWave scenarios, which we covered when discussing Figure 24 and Figure 25. We attribute the slightly lower than expected frame rate of 25 fps in the second bar from the right to the TCP ACK/NACK messages which are part of the uplink transmission. In the foreseeable future, we expect to observe the full 30 fps with this test scenario.

The results in Figure 29 provide additional information about the video performance with each test scenario. The figure shows the percentage of time the video was impaired or frozen (primary Y axis) and the number of times the video was impaired (secondary Y axis) during the test. A higher video impairment count isn't necessarily worse than a lower video impairment count if the percentage of time the video was impaired remained the same. For example, 10 seconds of impaired video in a 100 second test would result in an impairment rate of 10%. These impairments could occur all at once (10 seconds), there could be 10 impairments, each lasting 1 second, there could be 50 impairments, each lasting 200 milliseconds, etc. It is somewhat subject which scenario is better since some consumers might tolerate a single long freeze more than several short freezes while other consumers might favor several short freezes over a single long freeze. To us, the total impairment time is the key metric while the impairment count just provides additional visibility into how the impairments occurred.

Figure 29. Total Video Impairments per Test Scenario



Source: Signals Research Group

To close out our analysis of video performance in the uplink direction we include three figures which show still images of a different video that we used to evaluate the user experience while streaming to YouTube Live. With this video, we were able to analyze the video quality, or video mean opinion score (VMOS). Each of the following three figures includes three images: one image taken from the source video playing natively on the smartphone, one image of the video captured on the YouTube Live server after streaming it over a congested LTE network, and a third image of the video, also captured on the YouTube Live server, but in this case streamed over 5G NR mmWave. We tried as best as possible to show the same frame from the video with each image, but due to the capture rate of the video analysis platform, we were not always successful. We've also included the video quality score with each image. Although the relative quality of the images plays a big role in explaining the differences in the scores, a secondary factor is that the images do not completely align with each other.

Figure 30. Source Video versus LTE Loaded Video versus 5G NR + LTE Video, I

Source Video (VMOS = 4.94) | **LTE Video with Network Congestion (VMOS = 4.28)** | **5G NR Video with LTE Network Congestion (VMOS = 4.84)**

Source: Signals Research Group

Figure 31. Source Video versus LTE Loaded Video versus 5G NR + LTE Video, II

Source Video (VMOS = 4.71) | **LTE Video with Network Congestion (VMOS = 4.49)** | **5G NR Video with LTE Network Congestion (VMOS = 4.98)**

Source: Signals Research Group

Figure 32. Source Video versus LTE Loaded Video versus 5G NR + LTE Video, III

Source Video (VMOS = 5.0) | **LTE Video with Network Congestion (VMOS = 4.59)** | **5G NR Video with LTE Network Congestion (VMOS = 5.0)**

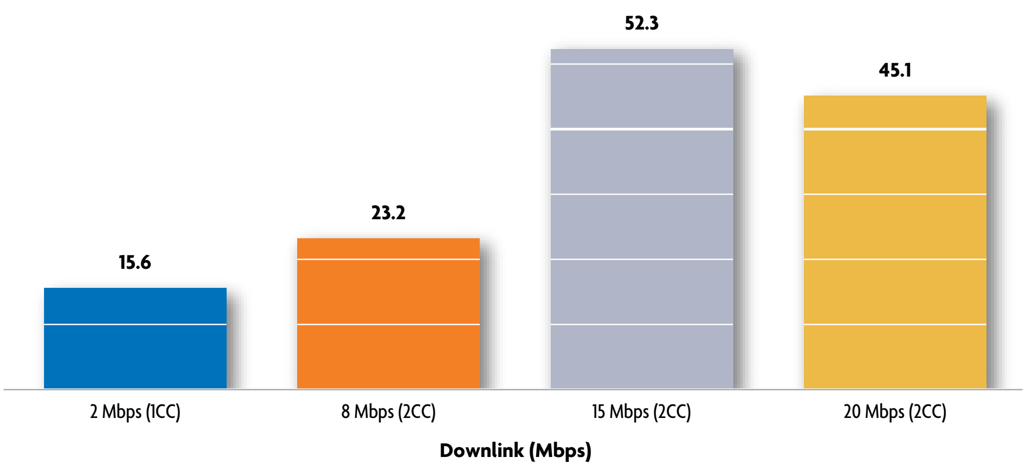
Source: Signals Research Group

3.3 Video Streaming Radio Network Requirements and the Impact of Network Loading – Downlink Specific

In addition to testing video performance in the uplink by streaming content to YouTube Live, we also tested video performance in the downlink direction. For these tests, we streamed a test video from the host server (Akamai) and then analyzed the network resource requirements and the video quality. This video streamed at a constant bit rate that ranged from 2 Mbps to 20 Mbps. At the start of the video there were several minutes where the video streamed at 2 Mbps, before increasing to the next bit rate threshold. This concept made it ideal when scoring video performance based on the bit rate of the video and the network loading conditions, both being variables that we could control.

Figure 33 shows the average physical layer throughput used when streaming the video with different bit rates. With a 2 Mbps video, the smartphone used a single LTE carrier, but with the higher bit rate videos it used carrier aggregation. One anomaly in the figure is that the physical layer throughput required for the 15 Mbps video was higher than the physical layer bit rate for the 20 Mbps. After further investigation we determined the physical layer throughput associated with HARQ (retransmissions) was much higher with the 15 Mbps video. It isn't entirely clear why the HARQ retransmission rate was higher, but it does explain why the physical layer throughput was higher with the 15 Mbps bit rate video than the 20 Mbps bit rate video.

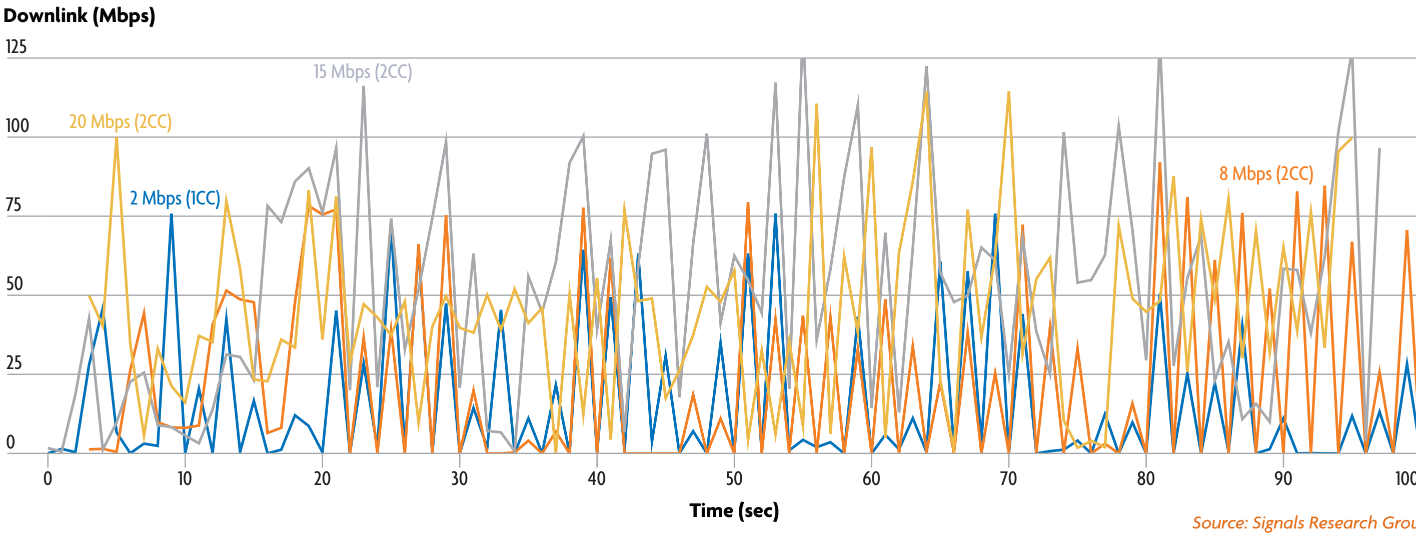
Figure 33. Physical Layer Resource Requirements per Video Bit Rate



Source: Signals Research Group

Figure 34 provides a time series plot of the physical layer throughput required to play the videos without interruption in an unloaded LTE network. Since the video player only allowed 3 seconds of video buffering in the phone's memory, the network needed to nearly continuously transmit video content – the time gaps between each transmission were roughly the same for all videos, but the magnitude of the throughput was much higher with the higher bit rate videos.

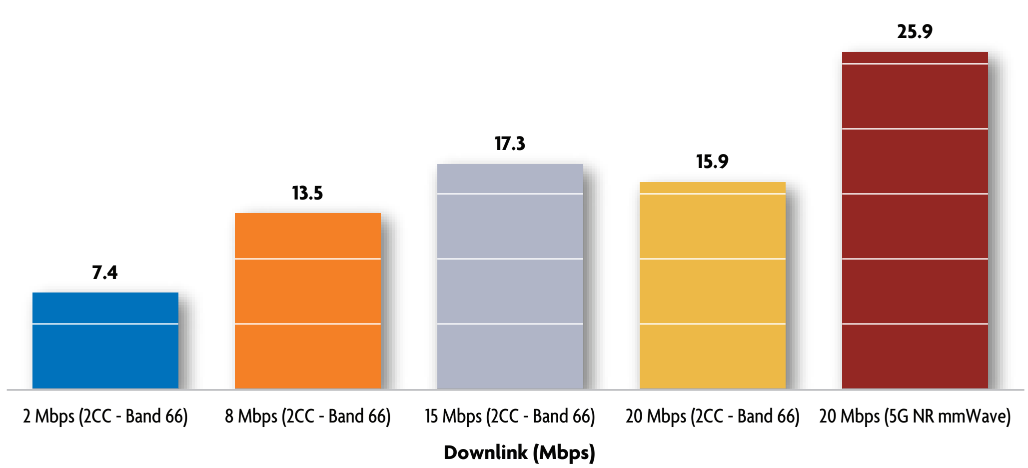
Figure 34. Physical Layer Resource Requirements per Video Bit Rate Time Series



Source: Signals Research Group

The physical layer throughput shown in Figure 35 stems from tests in which we locked the smartphone streaming the video content to Band 66, which also had 8 additional smartphones doing full buffer downlink data transfers (e.g., network loading). The figure also includes the physical layer throughput when we enabled 5G NR mmWave on the smartphone. Compared with the earlier figure, which showed average throughput in an unloaded network, it is evident the background traffic limited the bandwidth available for the video. By enabling 5G NR mmWave on the smartphone, the smartphone was able to take advantage of the additional bandwidth available over mmWave spectrum. The implication is that when the available bandwidth is limited,

Figure 35. Physical Layer Resource Usage per Video Bit Rate with Loading

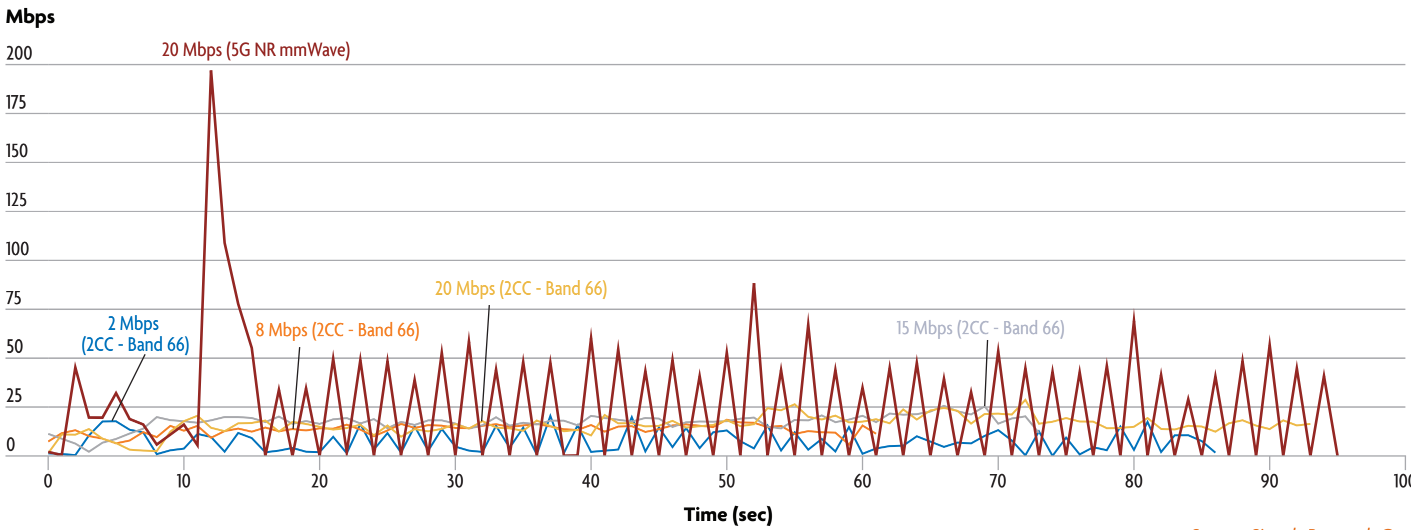


Source: Signals Research Group

the video user experience can be impacted, especially with higher bit rate videos. Later in this section, we show some examples of still images which show degraded video quality due to this phenomenon.

Figure 36 provides a time series plot of the physical layer throughput for the smartphone streaming the video, and finally Figure 37 shows the average throughput for the 8 smartphones which were receiving full buffer downlink data transfers during this test.

Figure 36. Physical Layer Resource Usage per Video Bit Rate with Loading Time Series

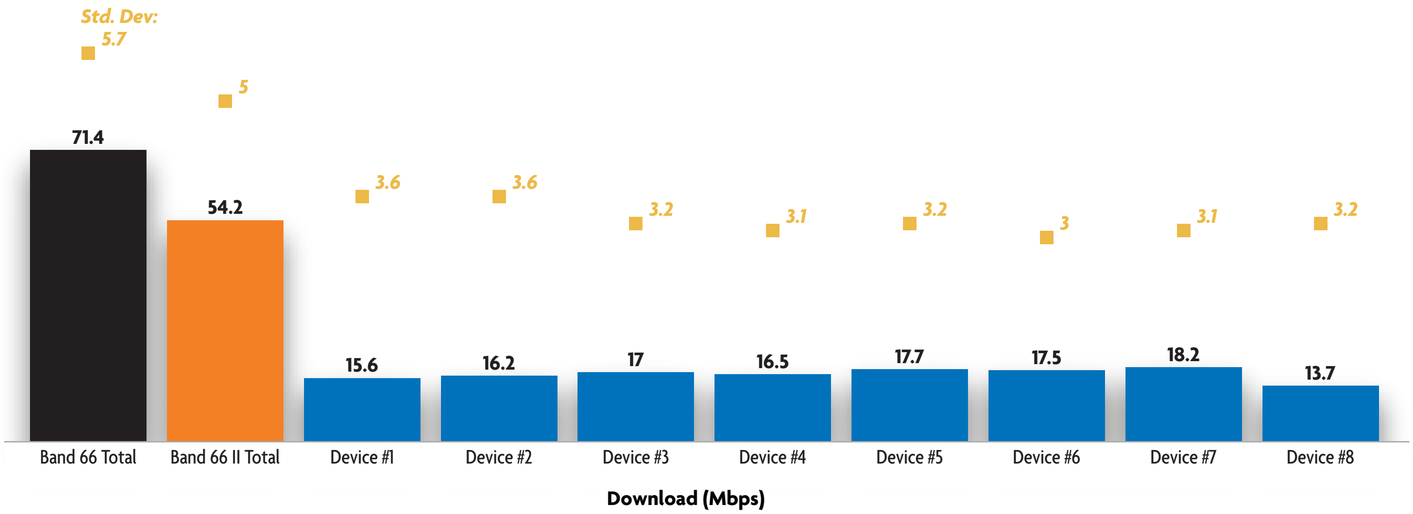


Source: Signals Research Group

We can draw a few conclusions from these figures.

- The average physical layer throughput used to support each video was lower with network loading than it was in an unloaded network. The lower throughput was due to network loading, meaning with the higher bit rate videos there weren't enough network resources to stream the video content without freezes (proven in a bit).
- The time series plot reveals the smartphones were almost always receiving data from the network so even in cases when there wasn't any video freezing, it is clear the network was being stressed. Note that when the smartphone streamed the 2 Mbps video that it used carrier aggregation in the loaded network scenario while in the unloaded network scenario it used a single radio carrier.
- The average downlink throughput for the additional 8 smartphones was sufficient for streaming a 10 Mbps video but not sufficient for the higher bit rate videos.
- When we streamed the 20 Mbps video over 5G NR, the physical layer throughput was sufficiently greater than 20 Mbps to avoid video freezes.

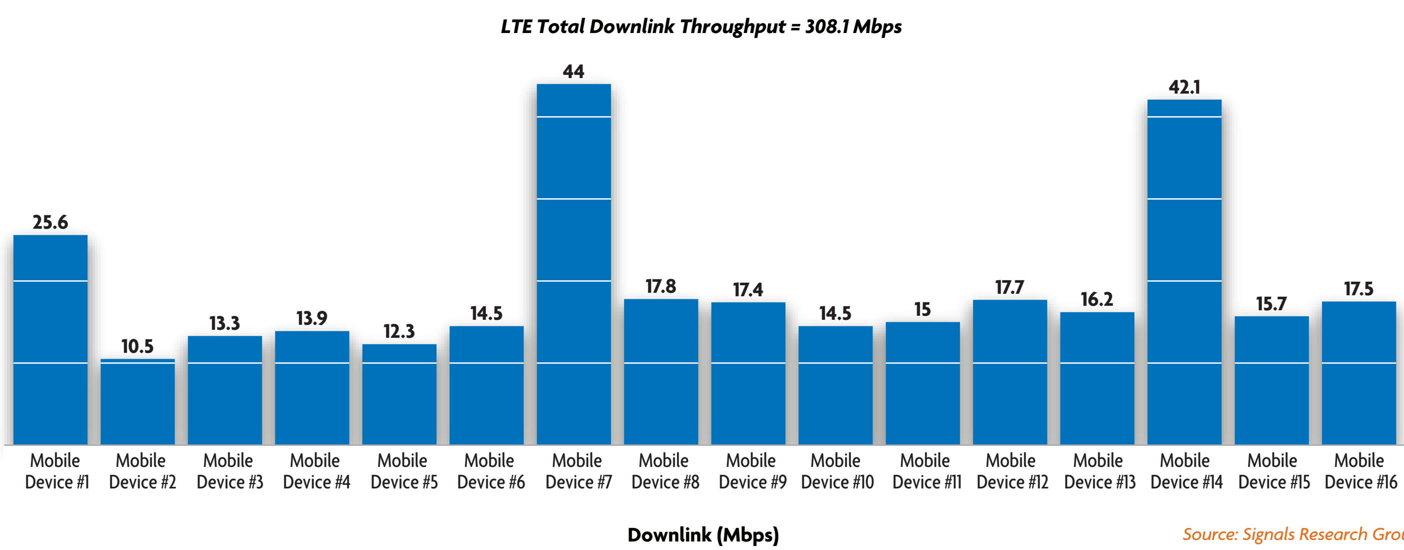
Figure 37. Average Physical Layer Throughput – 8 smartphones on Band 66



Source: Signals Research Group

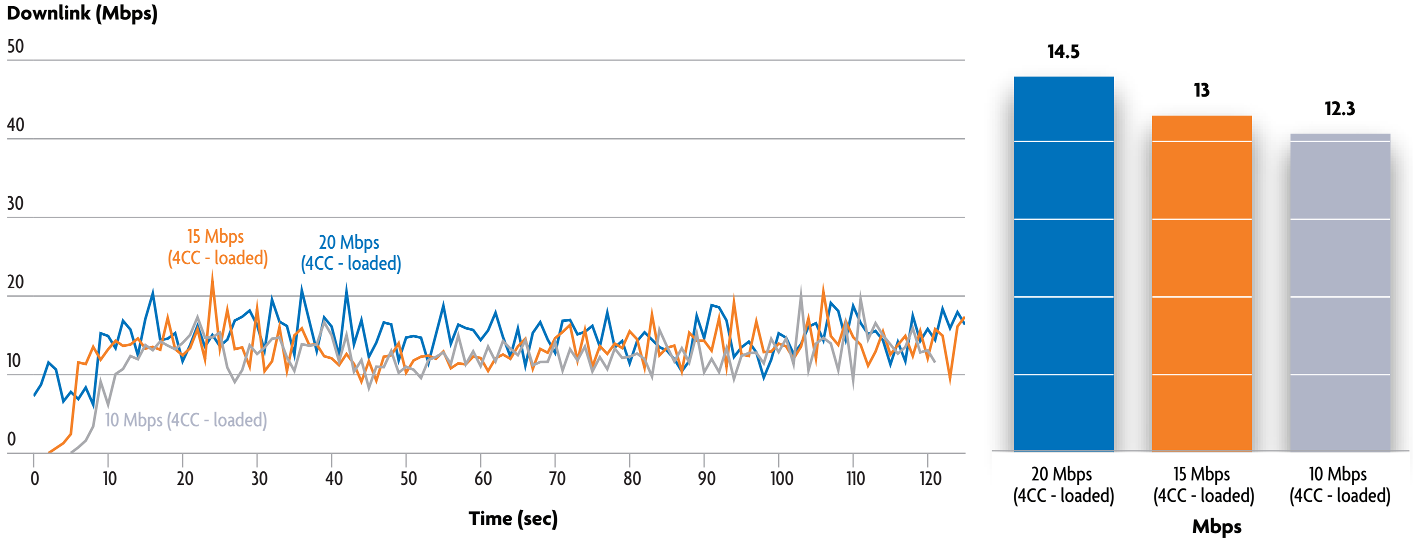
To conclude this section, we include results from some additional video streaming tests. For these tests, the LTE phones were allowed to use any and all bands. All smartphones used 4CCA. While these smartphones were doing full buffer downlink data transfers, we used an additional smartphone to stream the test video from the server. Figure 38 provides the average throughput for each smartphone doing full buffer downlink data transfers and Figure 39 provides a time series plot and average throughput for the smartphone streaming the video (10, 15 and 20 Mbps). With the 10 Mbps scenario there was some modest video buffering with the amount of video buffering increasing with the higher bit rate videos, as indicated in Figure 40.

Figure 38. Average Physical Layer Throughput – 16 smartphones on all LTE Bands



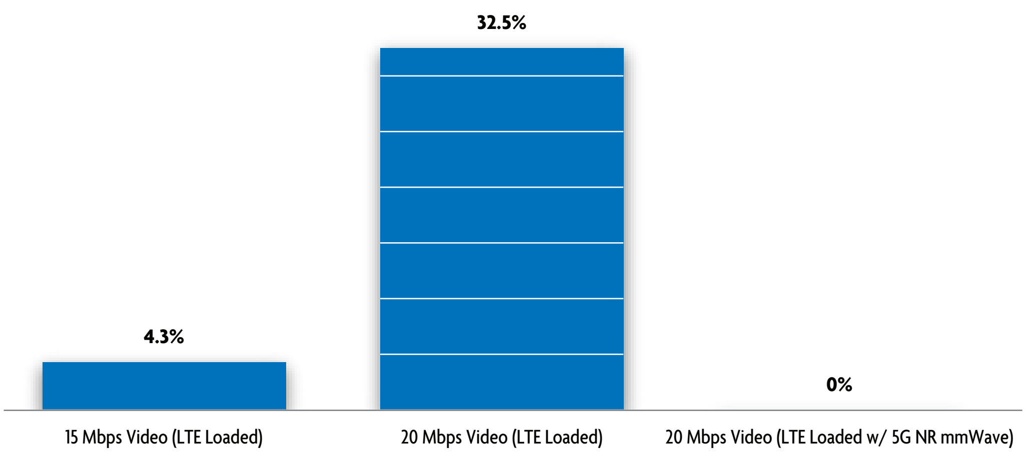
Source: Signals Research Group

Figure 39. Physical Layer Throughput – 10, 15 and 20 Mbps video streaming in a Loaded LTE Network



Source: Signals Research Group

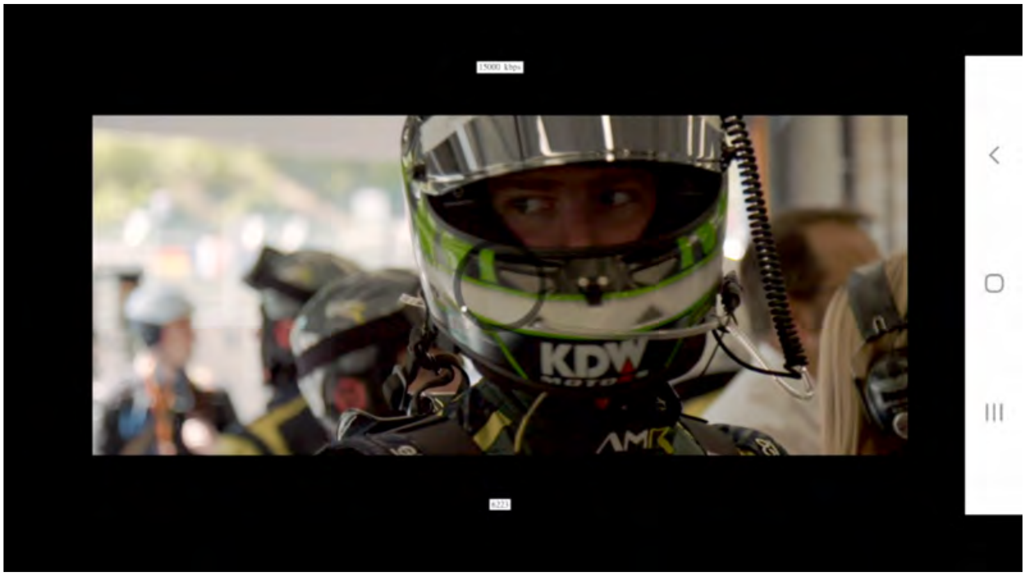
Figure 40. Video Performance Metrics



Source: Signals Research Group

Finally, Figure 41 provides a pictorial perspective of the user experience when the video buffering occurred. This particular image lasted for several seconds while we were treated to the spinning dial in the middle of the video image.

Figure 41. Video Buffering in a Loaded LTE Network



Source: Signals Research Group

4.0 5G NR mmWave in an Outdoor Environment in Europe

Until recently, all our 5G NR mmWave testing took place in the United States. One reason is that global travel restrictions for nearly the last two years have made it challenging to travel outside of the United States. Equally important, 5G NR mmWave deployments first occurred in the US so it made it relatively easy for us to test without having to travel outside of our home market. To quote a fellow Minnesotan, "the times, they are a-changin," and operators are beginning to deploy 5G NR mmWave networks around the world. As part of this study, we tested 5G NR mmWave in the Elisa network in Helsinki, Finland. The operator has deployed several sites in downtown Helsinki, thus giving SRG the chance to test 5G NR mmWave in Europe. Additionally, the operator also has a very robust 5G NR network deployed in Band n78 (3.5 GHz), so we were able to quantify the incremental benefits of mid-band 5G NR deployed on top of LTE as well as the incremental benefits of 5G NR mmWave deployed on top of both mid-band 5G NR and LTE.

LTE Bands

- Band 1 (2x20 MHz)
- Band 3 (2x20 MHz)
- Band 7 (2x20 MHz)

5G NR Bands

- Band n78 (1x100 MHz) – 80/20 DL/UL ratio
- Band n258 (8x100 MHz) – 80/20 DL/UL ratio

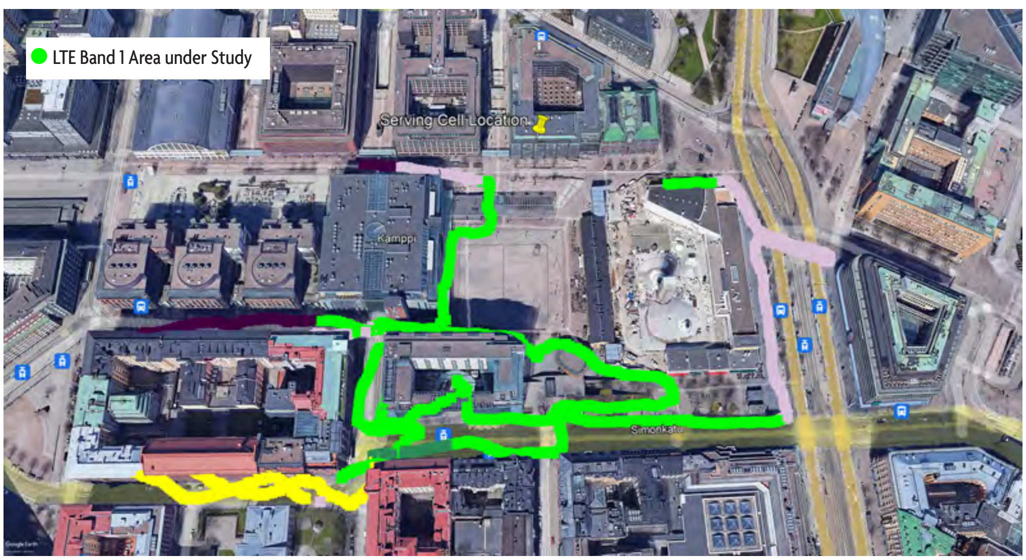
For this portion of the study, we used twenty Asus smartphones for Snapdragon Insiders with the Snapdragon 888 5G Mobile Platform, including the Snapdragon X60 Modem-RF System. For our tests, which took place in and around an outdoor plaza, we placed 18 smartphones in adjacent cells to generate interference in the cell under test. We then walked throughout the cell under test to determine the total capacity of the cell site with network loading – some of it due to other Elisa subscribers as well as to the network loading that we introduced with our smartphones.

We used resource block (RB) normalized throughput to determine the total capacity, or sector throughput, of the cell site. Specifically, we grossed up the measured throughput on our smartphone to account for the unassigned RBs, based on the assumption the network was assigning the RBs to other subscribers in the cell. To accurately calculate the total capacity of the cell site we geo binned the data so that we equally weighted all areas within the cell. Without geo binning, longer periods of time spent in an area with great performance (or bad performance) would erroneously influence the results. For an accurate calculation of total cell capacity, we needed the average performance across the cell with equal weighting of all areas.

4.1 LTE Network Capacity – Band 1, Band 3, and Band 7

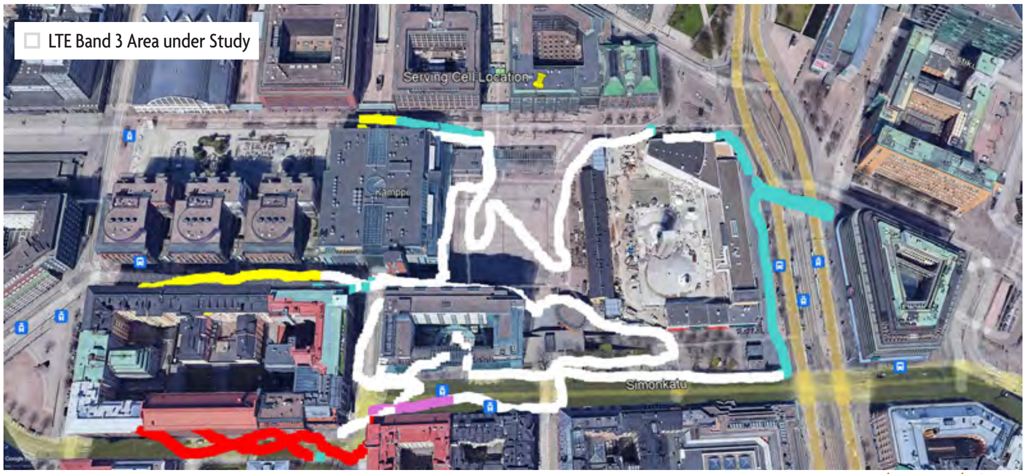
Elisa had 60 MHz of FDD spectrum for LTE in the downtown Helsinki area, comprised of Band 1 (20 MHz), Band 3 (20 MHz), and Band 7 (20 MHz). The first three figures show each PCI value encountered during our walk test of the plaza and the surrounding area. The PCI, or Physical Cell ID, is a unique value assigned to each cell sector (by LTE band). We use this information to determine which radio is providing the connection to our mobile device as well as the area covered by each LTE radio. The term PCI is also used with 5G NR. Based on these results, we determined the area where we wanted to conduct further tests with 5G NR Bn78 and 5G NR mmWave. To be more specific, the lime green circles (Band 1) in Figure 42 the white circles in Figure 43, and the purple circles in Figure 44 defined the LTE coverage area of each LTE sector. Although Band 7 will have a smaller coverage area than Band 1 and Band 3 when a network is deployed strictly for coverage purposes (i.e., maximum distances), this statement is not necessarily true when a network is deployed for capacity purposes, or when the distances between adjacent cell sites is much closer than it needs to be to provide ubiquitous coverage. Consequently, the coverage areas for all three bands were almost identical. In the case of Band 1, there are some missing data points in the center of the plaza, suggesting there wasn't any Band 1 coverage. There was Band 1 coverage, but the smartphone stopped using Band 1 in this area, hence we do not have any data points for this frequency in this area of the plaza.

Figure 42. Plaza Test Area – LTE Band 1 Coverage



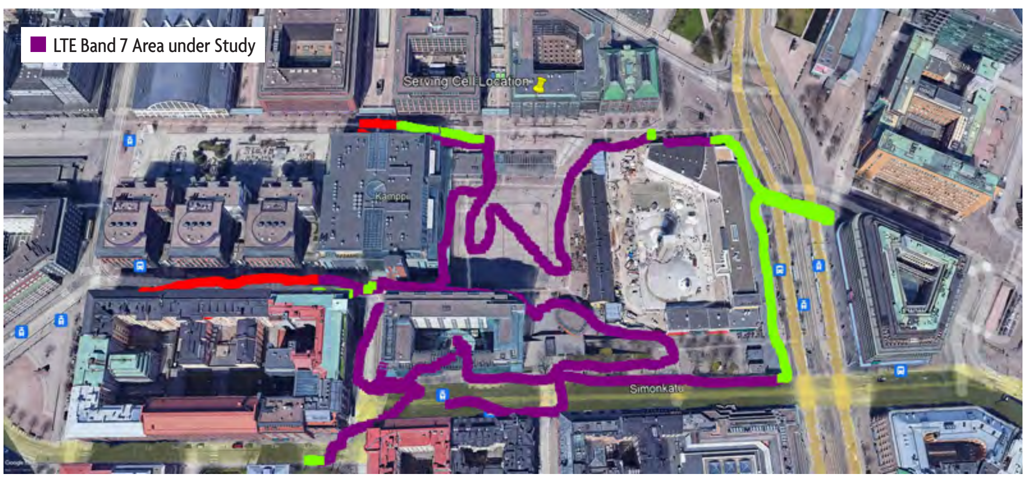
Source: Signals Research Group

Figure 43. Plaza Test Area – LTE Band 3 Coverage



Source: Signals Research Group

Figure 44. Plaza Test Area – LTE Band 7 Coverage

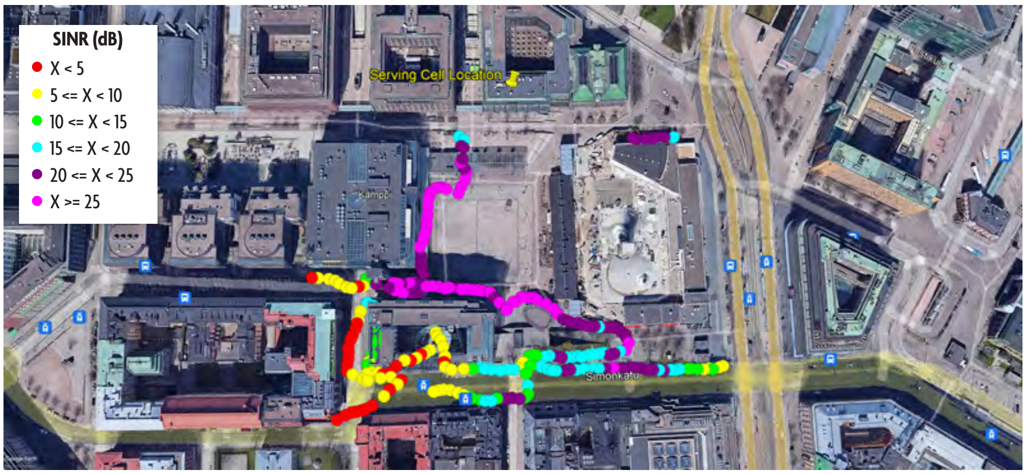


Source: Signals Research Group

When analyzing the results from the LTE walk tests we determined the measured throughput, even with RB normalization, was much lower than expected for the observed radio conditions, based on other testing we did in the Elisa network. Since we didn't want to understate the performance of the LTE network, we took a slightly different approach to determine the average LTE sector throughput in each band. We used the reported signal quality, or SINR, for each LTE band during the walk test and then used the expected RB normalized LTE throughput for that SINR value, as explained later in this section.

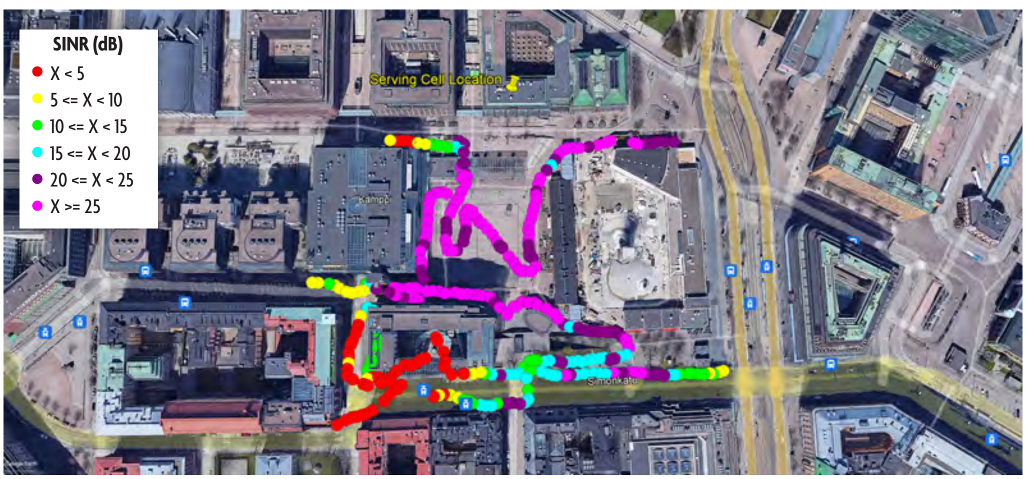
Figure 45 through Figure 47 provide geo plots of the binned SINR for each LTE band. These figures only show the SINR values for the cell sector we used in our testing since we filtered out all the results when we crossed into adjacent cells. In each of the three figures we also included the pertinent PCI value for each LTE band in the figure title. For example, as indicated in the figure title for Figure 45, PCI 130 was associated with LTE Band 1 in this sector.

Figure 45. Plaza Test Area – LTE Band 1 PCI 130 SINR



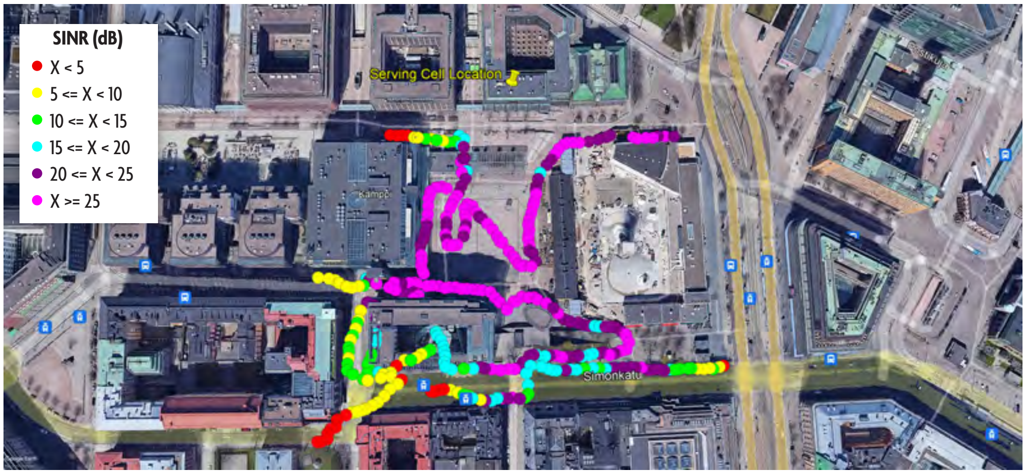
Source: Signals Research Group

Figure 46. Plaza Test Area – LTE Band 3 PCI 390 SINR



Source: Signals Research Group

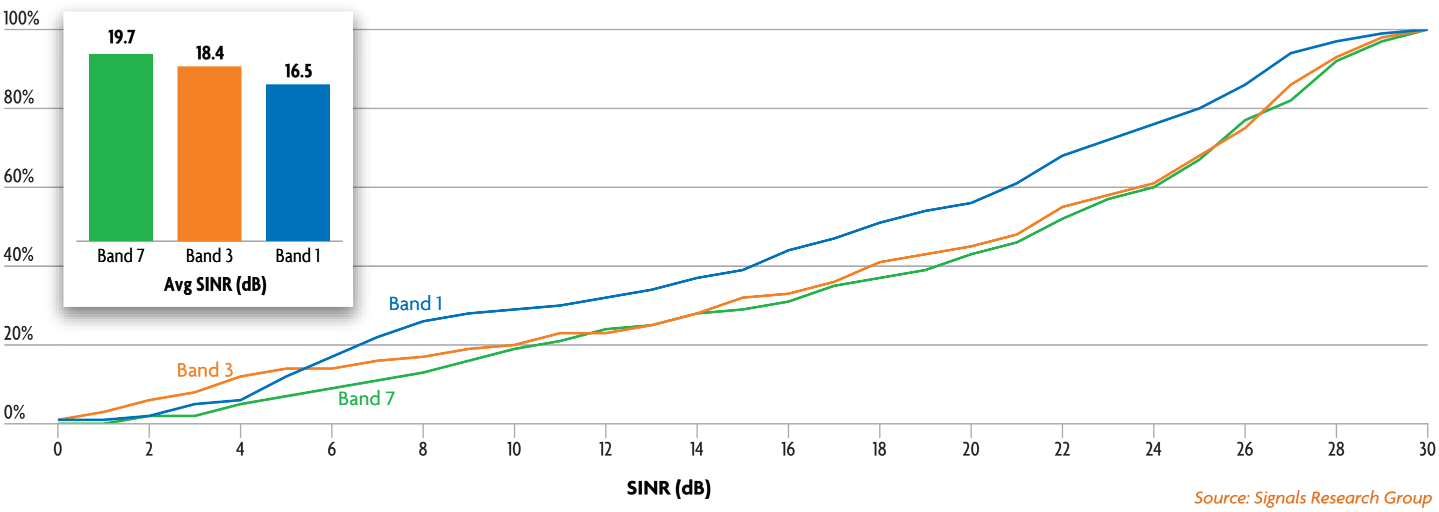
Figure 47. Plaza Test Area – LTE Band 7 PCI 223 SINR



Source: Signals Research Group

We binned the measured SINR values into 5x5 m grids and then averaged all SINR values to come up with an average SINR value for each band in the sector. Figure 48 provides the results from this analysis.

Figure 48. Cumulative Distribution and Average SINR by Frequency Band

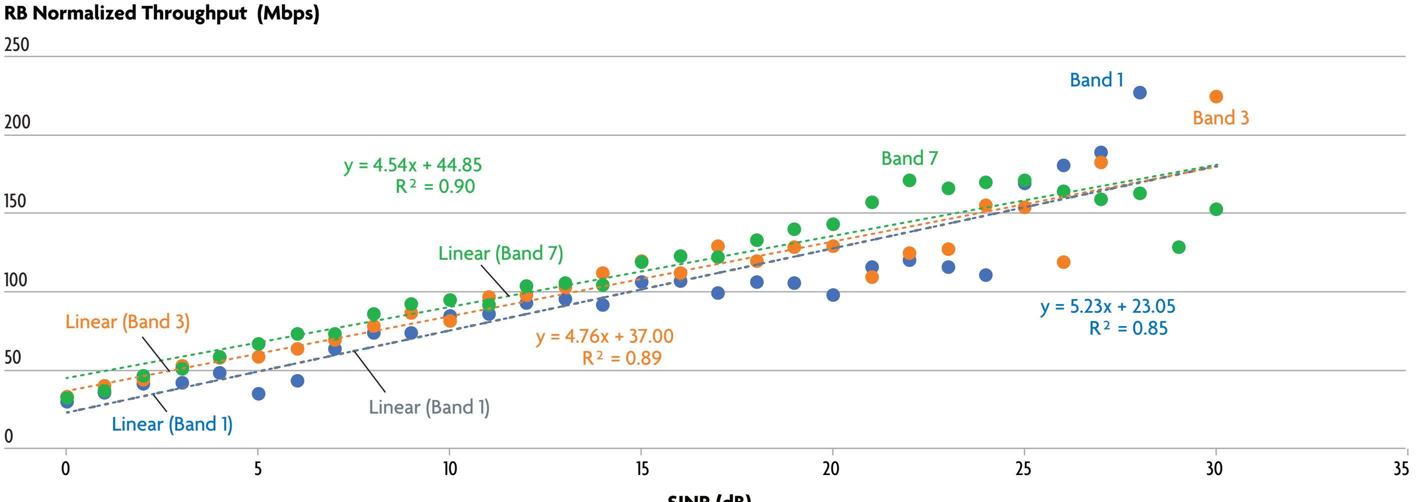


Source: Signals Research Group

When we were in Finland, we did additional testing of Elisa's network. The results from this testing indicated much stronger LTE performance than what we observed in our walk tests in the plaza for the radio conditions (SINR) we observed. We used this additional test data to determine the most likely throughput we should have obtained in the plaza walk tests. To do this analysis, we took the additional test data and plotted the RB normalized throughput as a function of the corresponding SINR value. Each data point in Figure 49 represents the average RB normalized throughput we observed for each SINR value we measured. Put another way, each data point (circle) in the figure can represent hundreds of measurements. Further, since we also

The close alignment of the data points (circles) and the high R2 values for each trendline also give us confidence that our methodology is sound.

Figure 49. LTE RB Normalized Throughput Versus SINR



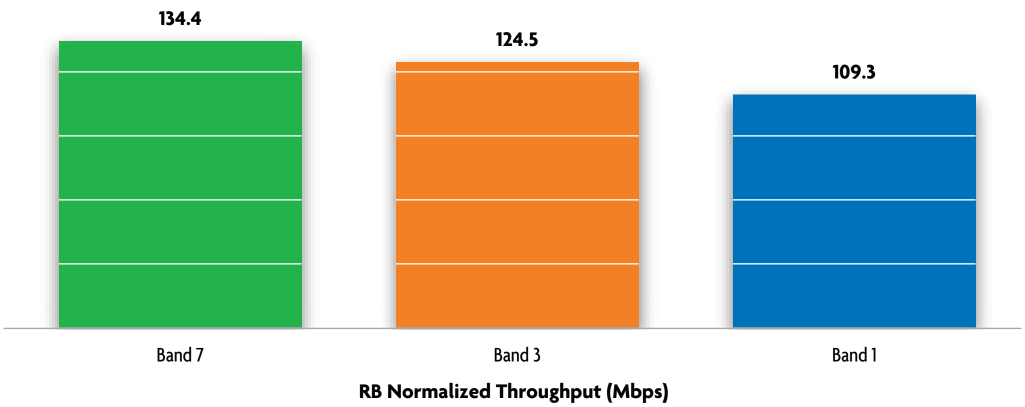
Source: Signals Research Group

time bin the collected data by taking an average value for the measurement reports, which occur every millisecond, it is safe to say that each data point (circle) in the figure is actually comprised of thousands of measurements. The close alignment of the data points (circles) and the high R^2 values for each trendline also give us confidence that our methodology is sound.

Using the information in Figure 48 and Figure 49, we calculated the average RB normalized throughput for each band, as shown in Figure 50. The summation of these three values (368.2 Mbps) represents the total throughput available over LTE in this area of the network, and for the three PCIs (LTE sectors) that covered this region of the network. Finally, Figure 51 provides the spectral efficiency (bps/Hz) for each LTE band. These results are different [better] than what we showed for our testing in Phoenix. The explanation is that in this case we used RB normalization with a single smartphone to determine the maximum spectral efficiency possible for the given SINR. In Phoenix, we used sixteen smartphones and then determined the spectral efficiency based on how the smartphones collectively used the available LTE network resources with full buffer downlink data transfers. Put another way, the Phoenix results incorporate potential scheduling inefficiencies, the uneven distribution of smartphones across available LTE channels, and possible drops in the data transfer rate between the LTE scheduler and the data source from the Internet.

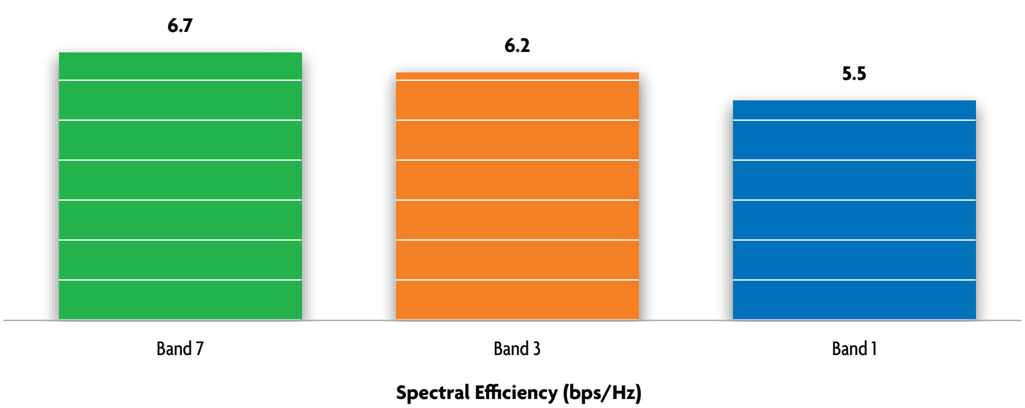
The LTE network in the plaza area supported a total of 368.2 Mbps, based on our analysis of the test data.

Figure 50. Average RB Normalized Throughput by Frequency Band



Source: Signals Research Group

Figure 51. LTE Spectral Efficiency by Frequency Band

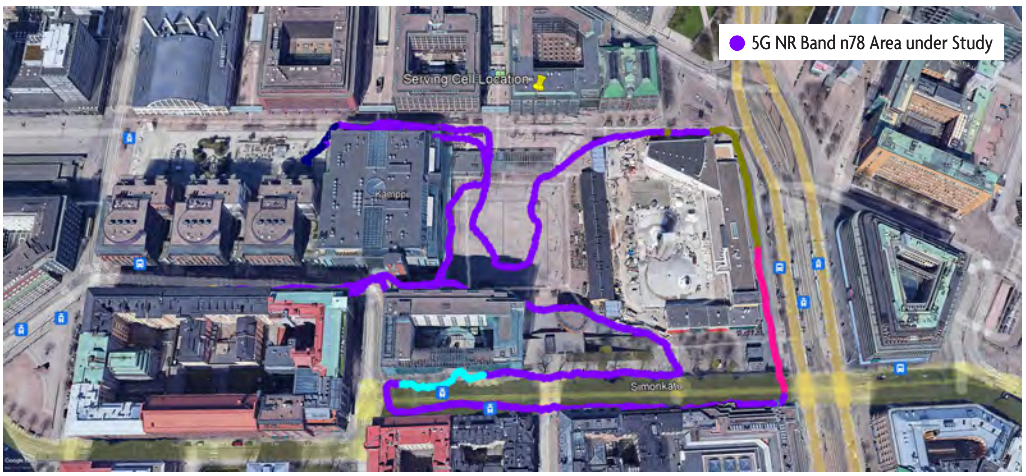


Source: Signals Research Group

4.2 5G NR Band n78 Network Capacity

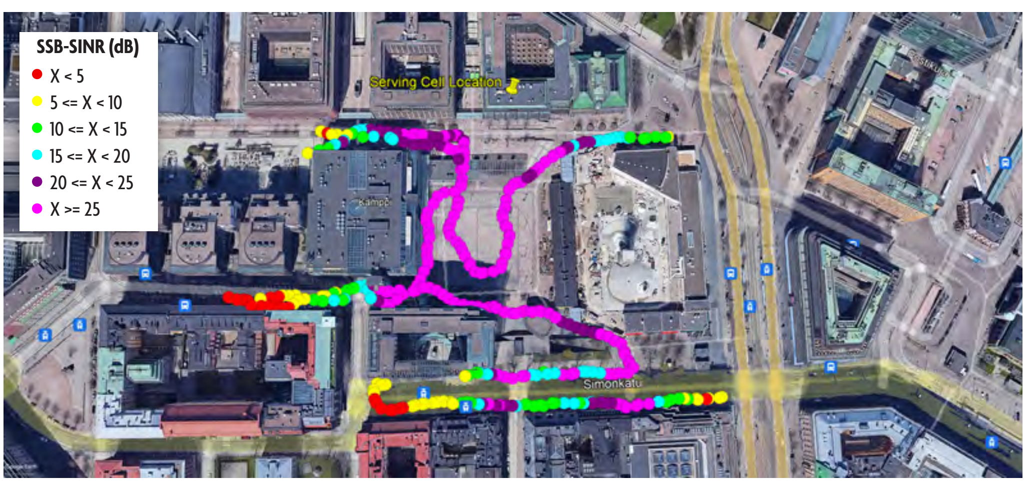
After finishing the LTE walk test, we repeated the test with Band n78 enabled on the smartphone. Figure 52 provides a geo plot of the Band n78 coverage with each colored circle representing a unique 5G NR PCI, or 5G NR radio / sector. In this figure, the purple color identifies the cell sector we analyzed for this study (PCI 158). One interesting observation is that the 5G NR coverage for Band n78 was very similar to what we observed with LTE – we did not include inbuilding testing as part of this study. This outcome isn't surprising given the density of the cell grid. Figure 53 illustrates the signal quality (SINR) for PCI 158, or the sector covering the plaza (the purple circles in Figure 52).

Figure 52. Plaza Test Area – 5G NR Band n78 Coverage



Source: Signals Research Group

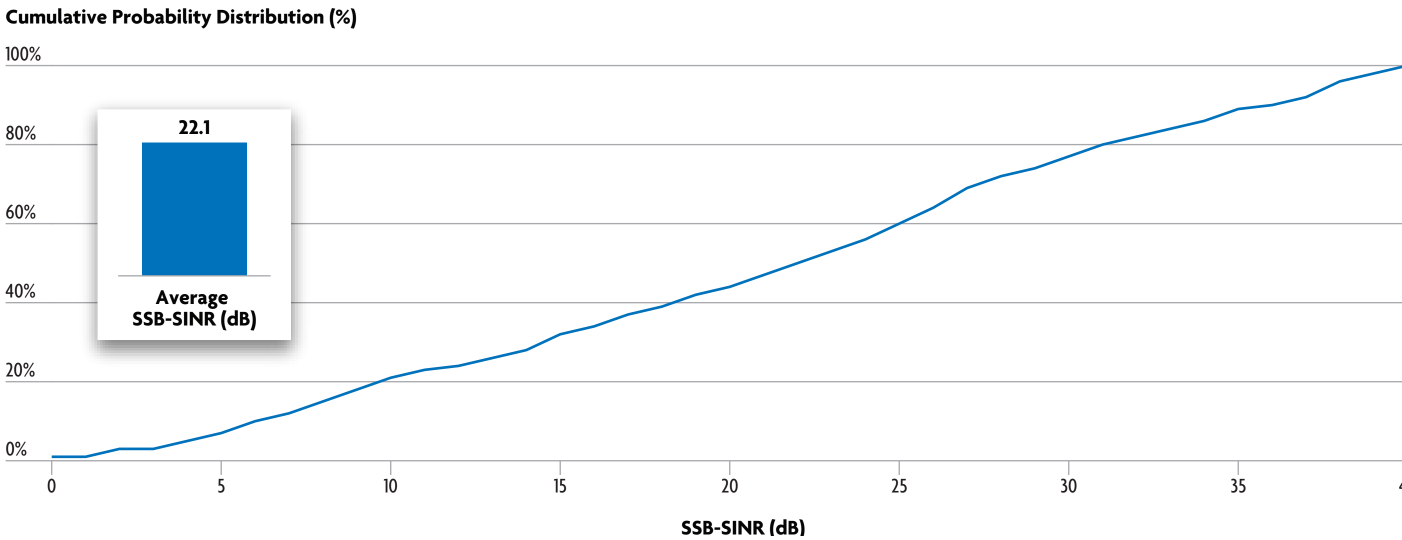
Figure 53. Plaza Test Area – 5G NR Band n78 PCI 158 SSB-SINR



Source: Signals Research Group

Figure 54 provides the cumulative distribution and average SINR for Bn78 (PCI 158 only).

Figure 54. Cumulative Distribution and Average SSB-SINR (dB) – Bn78

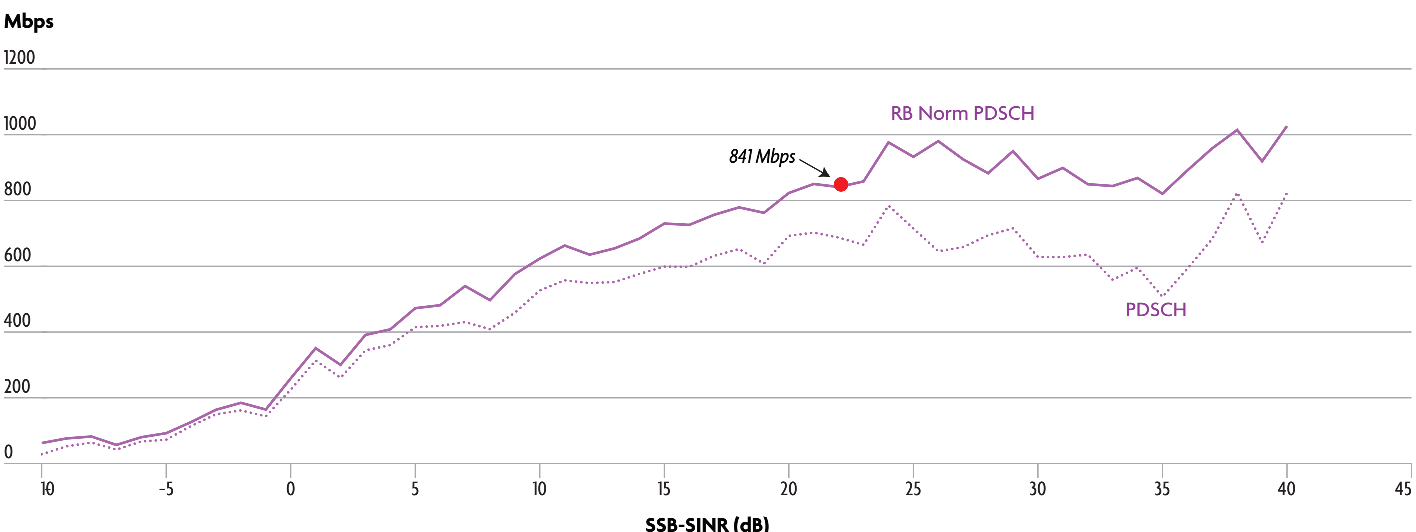


Source: Signals Research Group

Since we felt the Band n78 throughput was not as good as it should have been, based on other testing we did in Elisa's network throughout the week, we used the same methodology we used with the LTE analysis to calculate the optimal Band n78 RB normalized throughput for the given SINR conditions we observed. For this analysis, we leveraged extensive testing of Band n78 performance in central Helsinki. Figure 54 shows the relationship between RB normalized throughput and SINR. Like the LTE results, each data point (circle) in the figure represents an average of several hundred, if not several thousand, measurement points. In this figure, we highlighted the point on the RB normalized throughput curve which corresponds to the average SINR we observed in our Band n78 walk test around the plaza. Since we observed an average SINR of 22.1 dB, this equates to an RB normalized throughput of 841 Mbps. Put another way, 5G NR Bn78 increased the LTE network capacity by a factor of 2.3x. This outcome is a bit higher than anticipated. However, it is likely that interference in the neighboring cells (partly due to the interference we introduced as part of our testing) had a bigger impact on the LTE results than it did on the Band n78 results.

5G NR (Bn78) increased the LTE network capacity by a factor of 2.3x.

Figure 55. 5G NR Band n78 Throughput Versus SSB-SINR



Source: Signals Research Group

4.3 5G NR mmWave Network Capacity

After testing LTE and 5G NR Bn78, we enabled 5G NR mmWave on the smartphone and disabled Band n78 so the smartphone could only use the mmWave band (25 GHz or Band n258 with 800 MHz of total channel bandwidth). The 5G NR mmWave radios covering the plaza were in the same location as the LTE and Band n78 radios. One unique difference is Elisa had two 5G NR mmWave radios mounted on the side of the building with each radio assigned the same PCI. These radios were angled away from the building with approximately 70-80 degrees of separation. Figure 55 shows a picture of the two mmWave radios as well as the Band n78 radio. The LTE radios are in the same general location, but they are not visible in this picture.

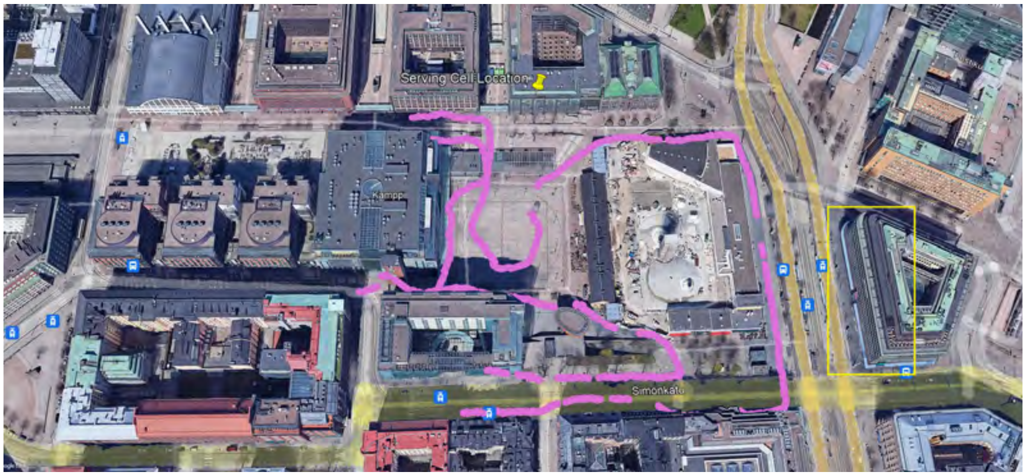
Figure 56 shows the 5G NR mmWave coverage area around the plaza. Since the two mmWave radios were assigned the same PCI (PCI 89), there is only a single color shown in the figure. The net effect of sharing the bandwidth between the two radios is that the capacity is lower than it would be with dedicated bandwidth for each radio. Secondly, the coverage is improved versus what would be possible with a single mmWave radio. In fact, comparing Figure 57 with the LTE and Band n78 coverage maps, it is evident the mmWave site provided coverage to areas around the plaza which were not covered by the LTE and Band n78 radio assets from the same location as the mmWave radios. These areas had coverage, of course, but the coverage came from different PCIs which were located elsewhere. The best example of this situation is the stretch along the major street on the right side of the picture. Although it isn't evident in the picture, the height of the buildings next to where we walked made it impossible to see the mmWave radios, or non-line-of-site conditions. We assume the mmWave signals reflected off the building highlighted in the figure.

Figure 56. 5G NR Radios

Source: Signals Research Group

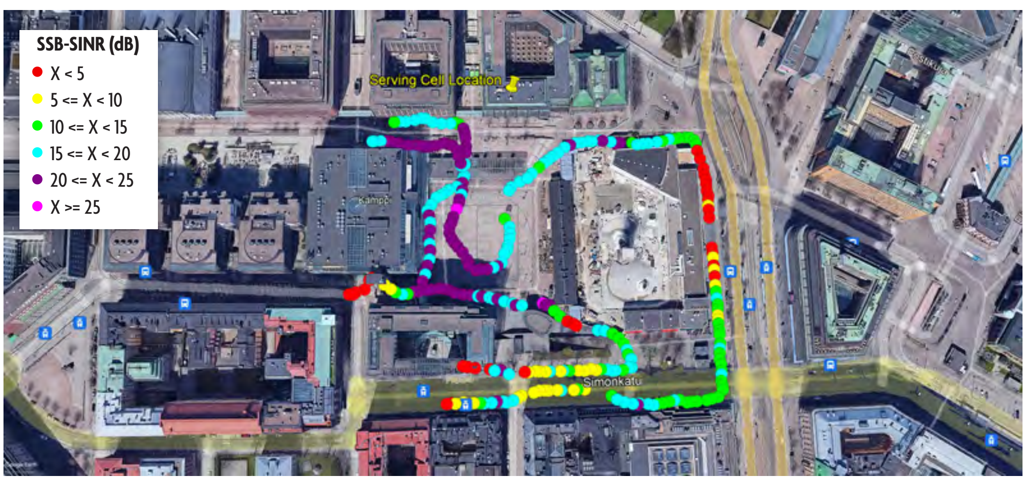
Figure 58 provides a geo plot of the SINR along the walk. Like the previous SINR plots, we geo binned the measured values in 5x5 m grids.

Figure 57. Plaza Test Area – 5G NR mmWave Coverage



Source: Signals Research Group

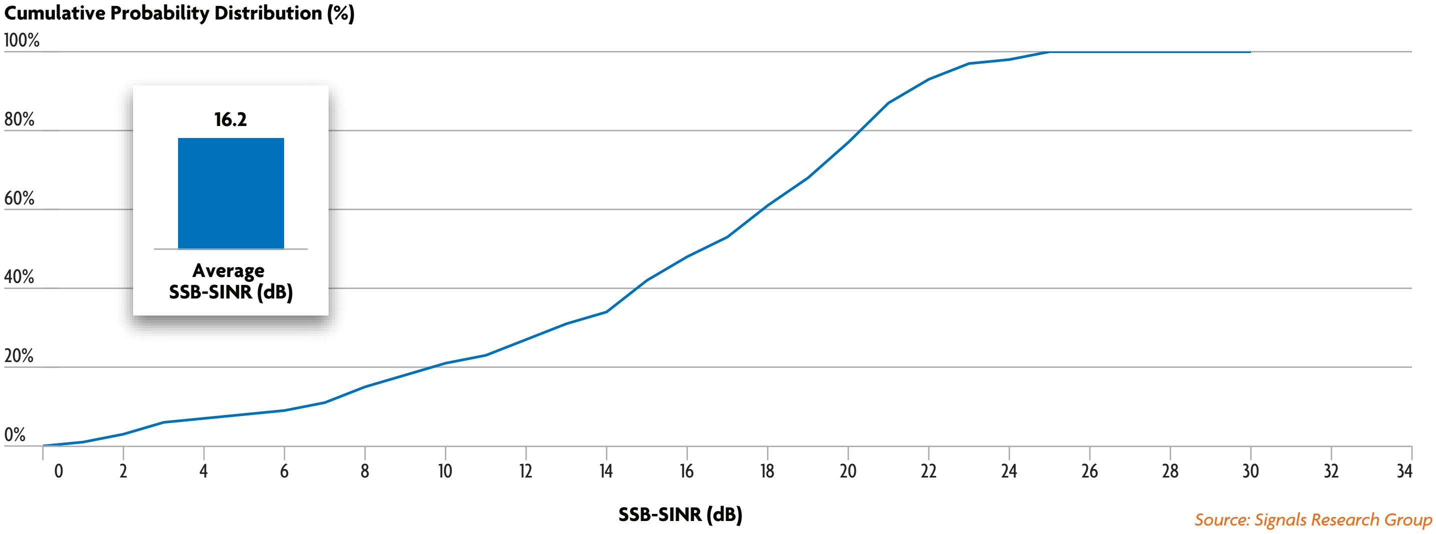
Figure 58. Plaza Test Area – 5G NR mmWave PCI 89 SSB-SINR



Source: Signals Research Group

Figure 59 illustrates the distribution of the SINR as well as the average SINR for 5G NR mmWave. The results include both mmWave radios.

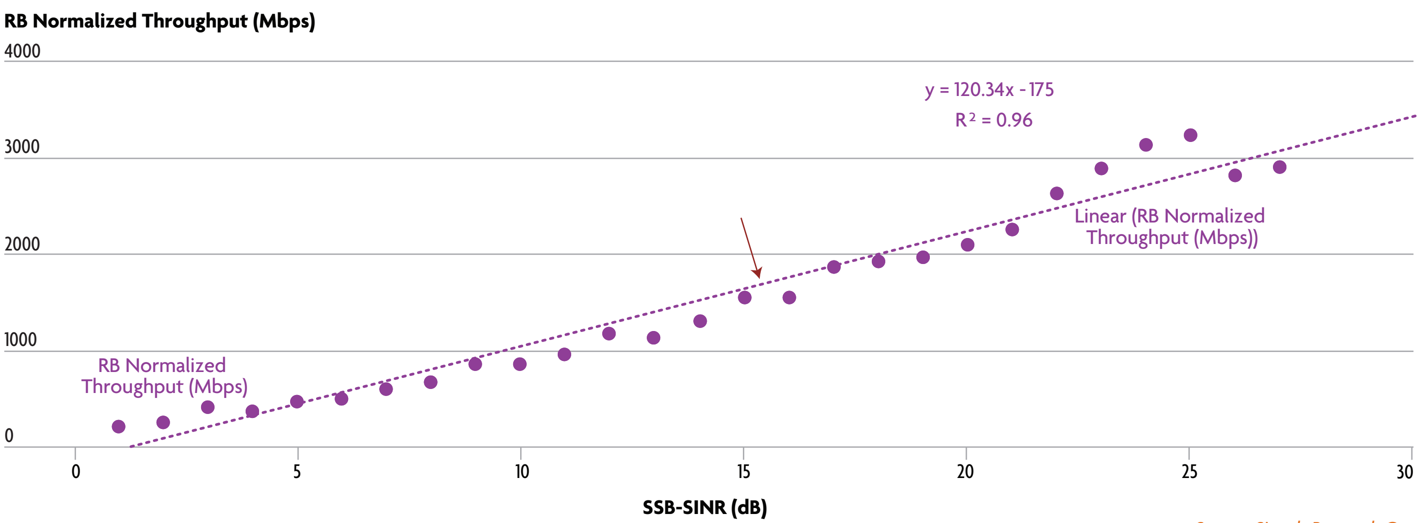
Figure 59. Cumulative Distribution and Average SSB-SINR – Band n258



Source: Signals Research Group

Figure 60 illustrates the relationship between the RB normalized throughput and the SINR. Since the average SSB-SINR, based on geo binning the data, was 16.2 dB, we know the average RB normalized throughput during the walk was 1,775 Mbps. In a separate test we obtained an average RB normalized throughput of 2,275 Mbps, however, many of the measurement points were missing corresponding GPS coordinates. Since we weren't able to apply our area binning methodology to this test result, we elected to use the more conservative result (1,775 Mbps) we obtained.

Figure 60. 5G NR mmWave RB Normalized Throughput Versus SSB-SINR

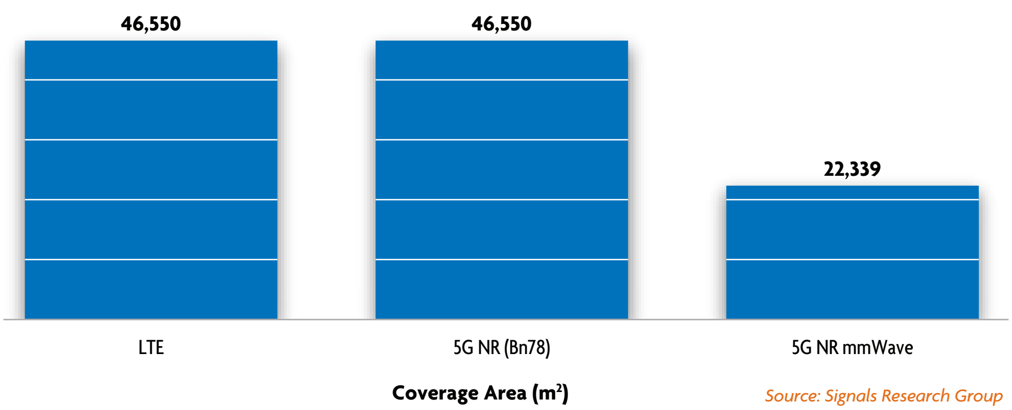


Source: Signals Research Group

The implied spectral efficiency from this more conservative value is lower than expected. However, it is also important to realize we were testing a single mmWave site and frequently walking at the edge of cell [if not out of the coverage area] where the SINR is sub-optimal. In a commercial mmWave deployment with multiple site locations, this situation is less pronounced and the corresponding spectral efficiency / average throughput would be higher than what we observed.

As the next step in our analysis, we calculated the LTE and 5G NR coverage areas using the geo plots we created with Google Earth. Since we didn't have the ability to enter some of the buildings within the test area, we don't have any knowledge about the inbuilding coverage. Given the close proximity of the cell site and the network coverage we observed outside the buildings during our walk, we assumed the LTE bands and Band n78 provided very similar coverage inside the buildings. To the extent there were "dead zones" the size of these areas relative to the outdoor areas where we knew there was coverage was very modest. For 5G NR mmWave, we assumed there wasn't any indoor coverage, even though we did some video testing while indoors, albeit relatively close to the windows. Figure 61 shows the calculated coverage areas for LTE and 5G NR. For LTE and Band n78, we included all indoor and outdoor areas within the area covered by each radio (PCI). For 5G NR mmWave, we only included the outdoor areas where PCI 89 provided coverage along our walk.

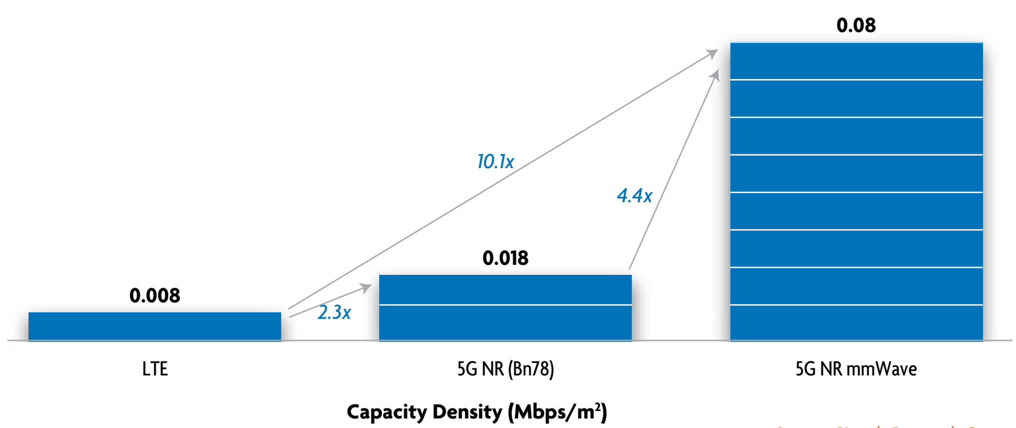
Figure 61. LTE and 5G NR Coverage Areas



Source: Signals Research Group

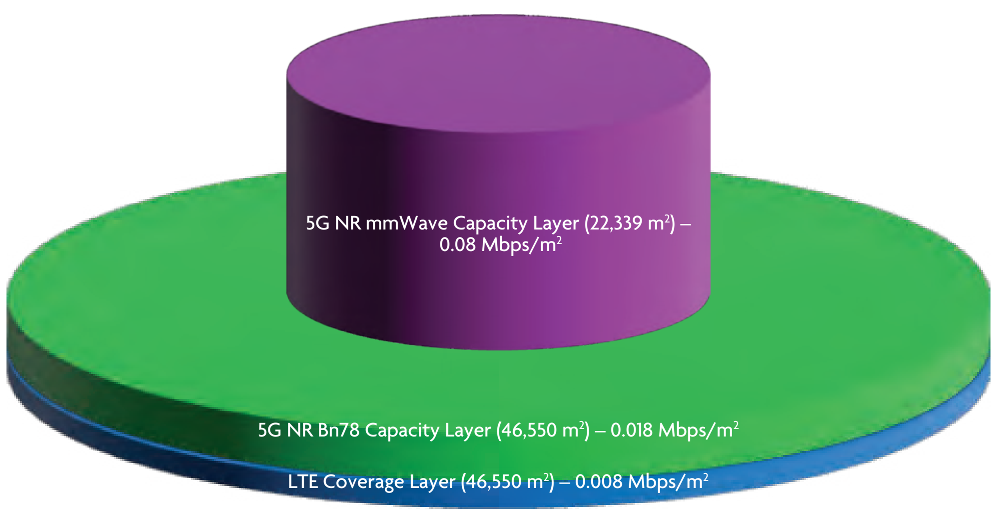
We then calculated the capacity density of each technology, or the total capacity (Mbps) divided by the total coverage area. The results from this analysis are shown in Figure 62. Based on our analysis, 5G NR Band n78 increased the capacity density by 2.3x versus LTE. Likewise, 5G NR mmWave increased the capacity density by 4.4x versus 5G NR Band n78 and by 10.1x versus LTE. Figure 63, which we also included in the executive summary, provides a pictorial view of the results. Worth noting, the layers of the cake are drawn to scale, and the 5G NR mmWave capacity value uses the more conservative result that we obtained in our testing.

Figure 62. LTE and 5G NR Capacity Densities



Source: Signals Research Group

Figure 63. LTE and 5G NR Capacity Densities



Source: Signals Research Group

5.0 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 leverage high bandwidth dedicated servers to generate reliable and sustained data transfers when doing our tests. From our experiences, it is critical that we conduct sustained downlink/uplink data transfer tests since lengthy data transfers are critical when evaluating network performance over a large area, including with mobility. Short data transfers, which are used with some popular measurement applications, do not suffice since their only practical purpose is to measure network conditions while stationary. We have also observed that operators rely to heavily on test servers located within their data centers. While this approach provides the highest possible data speeds over the radio access network, it can mask performance issues pertaining to how the data traffic gets to and from the Internet.

We've worked with Accuver Americas since we did our first LTE benchmark study in 2009. For this study, we used 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. We used two XCAL-Solo units while walk testing in Helsinki. We used XCAL-M in our testing of the Verizon network. XCAL-M is a software-based application that runs on a standard Windows PC. With XCAL-M we logged the performance of four smartphones on each PC, although the software supports even more smartphones per PC. We used the company's XCAP post-processing software to analyze the chipset logs that we captured.

We've worked with Accuver Americas since we did our first LTE benchmark study in 2009.

Our collaboration with Spirent Communications goes back to 2006 when we did the industry's first independent benchmark studies of 3G chipsets. For the last several years we have been using the company's Umetrix Data platform to generate high bandwidth data transfers during our tests. For the testing we did in Arizona we used a Umetrix data server located in California while for our testing in Finland we used a Umetrix data server located in Amsterdam. The servers, with 10 Gbps backhaul, support HTTPS, HTTP and UDP protocols, supporting downlink, uplink, or simultaneous downlink/uplink data transfers. Additionally, it is possible to set fixed rate data transfers (e.g., 5 Mbps or 30 Mbps), and we used this capability when artificially loading the network in Helsinki. Lastly, we used the Umetrix video platform when analyzing the video performance in this study.

Our collaboration with Spirent Communications goes back to 2006 when we did the industry's first independent benchmark studies of 3G chipsets.

We binned the logged chipset data into one-second time increments, thus making it more manageable to analyze the data. Since network parameters are literally reported at the millisecond level and they are constantly changing, even when standing at a fixed location, a single measurement point in a log file can be based on nearly 1,000 samples. When analyzing the results from our testing in Helsinki, we needed to use average performance across the entire sector we tested. Therefore, we also geo binned the data into 5x5 m grids to ensure we accurately captured the network performance without overweighing or underweighting parts of the test area.

We frequently use resource block (RB) normalized throughput in our analysis. RB normalized throughput adjusts the measured throughput to account for unassigned RBs. Unassigned RBs (e.g., RBs that are not being allocated to our smartphone) could be going to other smartphones in the sector or there could be insufficient data in the eNB/gNB scheduler. With RB normalized throughput we are able to depict the full capabilities of the network.

For the video analysis, we used specialized test videos with inserted markers to precisely evaluate the video delivery performance (frame rate, freezes/buffering, impairments, etc.). Figure 27 provides a still image that we used for our YouTube Live testing that we did to evaluate uplink performance. For these tests, we streamed a live session to YouTube and then evaluated the video performance, based on playing back the video on the YouTube server and scoring the performance with the Umetrix data platform.

We also used a non-reference video to evaluate video performance in the downlink direction. Figure 30 provides a still image of this video. For the downlink video testing, the video was hosted on an Akamai server to replicate a real-world scenario. The video was divided into several segments, based on the fixed bit rate of the video, which ranged between 2 Mbps and 20 Mbps. One additional attribute for the downlink video tests is that the memory buffer was limited to 3 seconds to limit precaching of the content and to better replicate a true video streaming user experience.

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