A GLOBAL PERSPECTIVE OF 5G NETWORK PERFORMANCE

OUR ANALYSIS OF NETWORK PERFORMANCE AND USER EXPERIENCE RESULTS FROM SUB-7.125 GHZ AND MILLIMETER WAVE 5G NETWORKS IN EUROPE, ASIA, AND NORTH AMERICA

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We wrote this whitepaper on behalf of Qualcomm. However, all testing, except the European testing, stems from testing and subsequent analysis that we did on our own for publication in our *Signals Ahead* research product over the last eighteen months.

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

Since the first commercial launches in April 2019, 5G has matured, the device ecosystem has expanded, and operators around the world have launched commercial services using a mix of mid-band and millimeter wave frequencies. Through the course of doing independent benchmark studies for our *Signals Ahead* research publication, we have established a wealth of experience on how 5G networks perform on a global basis. We've characterized 5G fixed and mobile millimeter wave networks, including in-building coverage, and we've traveled to Asia and Europe to understand how operators have deployed 5G in mid-band spectrum and how their networks are performing.

In this whitepaper, we've summarized several of our findings and observations, which we have previously published on our own. Although it is barely six months into a multi-year lifecycle that will extend well into the next decade, 5G is already starting to deliver on its promises. Near-term and more futuristic features and capabilities will further enhance 5G and the overall user experience.

- 5G-enabled smartphones are achieving substantially higher data speeds than their LTE brethren on a global basis. Depending on various factors, including loading on the LTE network and the amount of LTE and 5G bandwidth available, we've observed average gains of at least 2x with peak performance gains of 10x, or even higher.
- In capacity-constrained LTE networks which also support 5G, the user experience is meaningfully enhanced with a 5G-capable smartphone. In addition to faster download times (5x or more), a 5G-capable smartphone improves video streaming with higher quality video resolution and reduced susceptibility to video stalls.
- Millimeter wave is more resilient to the surrounding environment than generally perceived. Directional beams and reflections play a key role and they can lead to very interesting findings, including strong millimeter wave signals where they are least expected. Quite often, when someone notices the absence of a 5G millimeter wave signal it is due to other factors involving the LTE network, which can be addressed through optimization.
- 5G millimeter wave deployments are already occurring with very favorable results. We've documented close to ubiquitous coverage within the seating area of one NFL stadium, along with data speeds that frequently exceeded 1 Gbps and peaked at just over 2 Gbps.
- 5G can be more energy efficient than LTE, especially when supporting high bandwidth applications. With lower bandwidth applications, LTE tends to have the advantage, however, our analysis indicates that a full day's battery life is highly likely with most usage scenarios. Activities, other than data connectivity, tend to have the biggest impact on the battery life.

Although 5G performance is quite good today, there are opportunities for improvement that are forthcoming in the coming months and years. Examples include:

- Leveraging lower frequencies for 5G, which will also help improve performance at millimeter wave frequencies;
- Increasing the bandwidth of 5G radio channels to deliver higher peak data speeds (multi Gbps);
- Improving modem efficiency by integrating 4G and 5G processing requirements into a single chipset, as well as tighter interworking between the modem and RF front end;
- Optimizing how 5G and 4G networks work together, ultimately achieving increased availability and reliability of the 5G network, as well as higher user data speeds; and
- Using a Standalone (SA) architecture with a 5G core network to support ultra-reliable and low latency applications that can better serve new vertical markets.

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Background

Signals Research Group (SRG) has been conducting independent benchmark studies of chipsets, devices 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 tested Verizon's commercial 5GTF network (Oct 2018) with consumer premises equipment (CPEs) as well as the operator's 3GPP-based 5G millimeter wave networks in Chicago, Illinois and Minneapolis, Minnesota (Apr 2019), including the operator's indoor 5G network at US Bank Stadium, home of the Minnesota Vikings NFL football franchise (Oct 2019). In the US, we've also tested the T-Mobile 5G millimeter wave network in New York City (Aug 2019) and Sprint's 5G (2.5 GHz) network in Chicago. In Asia, we've tested SK Telecom's 5G (3.5 GHz) network in Seoul, South Korea (Jul 2019). As part of this study, we tested EE's 5G (3.5 GHz) network in Central London and Swisscom's 5G (3.5 GHz) network in Bern, Switzerland.

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 write a paper which highlights 5G network performance. One reason, we suspect, is that our testing and analysis provide credible information that we can back up with supporting data. Frequently, casual "testers," such as media and bloggers, publish results and analysis from their experiences in a 5G network that misrepresents how the networks are really performing.

Since we hadn't done any 5G testing in Europe, we ventured off to London and Bern in mid-August to include network performance and user experience results in this report. All other figures in this report and the subsequent analysis stem from earlier published research in *Signals Ahead.* For these studies, there is never any vendor involvement although as a courtesy and to hopefully gain some initial insight, we pre-brief the mobile operator prior to publishing the report.

5G Networks Provide an Important Capacity Layer to Existing LTE Networks

In this section, we summarize 5G network performance based on testing that we've done in Asia, North America and Europe. Since we try to conduct these studies soon after an operator has launched commercial services (sometimes even before the network is commercial), the results in this section could understate the current state of network performance, not to mention continuous improvements that are inevitable in the coming months and years.

In June 2019, we tested SK Telecom's 5G network in Seoul, South Korea. SKT is using 100 MHz of spectrum in Band n78 (3.5 GHz), which it pairs with its 75 MHz of FDD spectrum (Band 5, Band 3, Band 1, and Band 7), which enables 5CCA (5 component carrier aggregation). Although we were only in the country for a few days, during which time we enjoyed more than our fair share of Korean barbeque, we still transferred at least 2.3 TB of data. We used an LG V50 (5G-enabled) and an LG G8 (LTE Only) smartphone for the study with all testing taking place in and around the Gangnam District. By using two smartphones downloading data concurrently, we could quantify the performance differences of the two smartphones/technologies over a complete range of network conditions.

We did drive testing at night, when the roads were less congested, and we did pedestrian testing in the late afternoon and early evening hours. The results from a 4.6 kilometer walk test near COEX illustrates the typical results that we observed in our testing. During this test we transferred 192.8 GB of data between the two phones. Figure 1 shows the walk route that we used and Figure 2 shows where the LG V50 was using a 5G radio bearer. One reason why the smartphone wasn't always connected to the 5G radio bearer is that it will only connect to 5G when it is receiving or transmitting data. As explained in the test methodology section, although we use lengthy data transfers there are brief periods in between each session when no data transfers occur. We discuss another important explanation for the periodic absence of the 5G radio bearer later in this paper.

Figure 1. Pedestrian Route - COEX

Source: SA 07/03/19: "K-Pop Meets 5G" – Figure 28

Figure 2. 5G Active - COEX

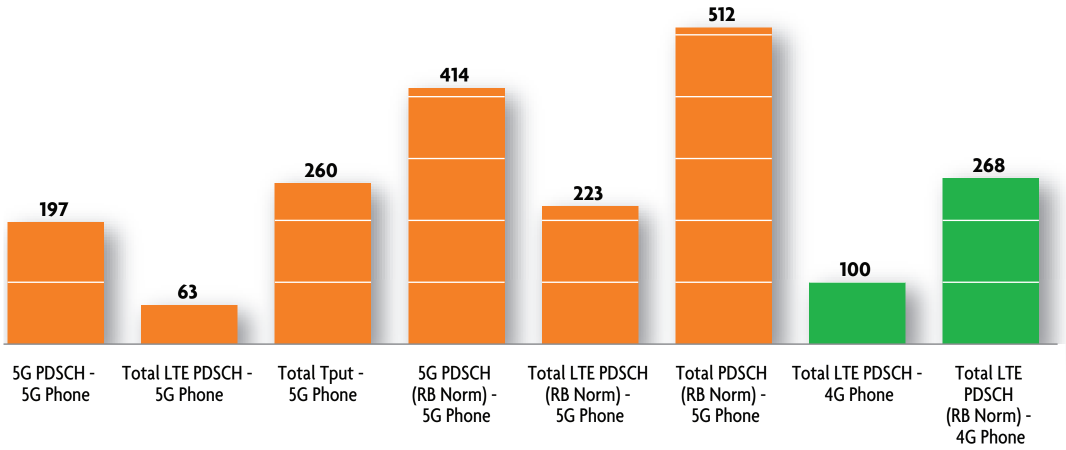
Source: SA 07/03/19: "K-Pop Meets 5G" – Figure 29

Figure 3 summarizes the results from this study with a focus on data speeds. We generally prefer to look at other performance parameters involving signal strength (RSRP) and signal quality (SINR) or the efficiency of the data transfers (MCS), however, in order to appeal to a larger audience, we are focusing the results in this paper on well-understood performance metrics.

The 5G-enabled smartphone achieved 2.6x faster data speeds than the LTE-Only smartphone.

As shown in the figure, the 5G-enabled smartphone achieved 2.6x faster data speeds than the LTE-Only smartphone (Total Tput – 5G Phone versus Total LTE PDSCH 4G Phone). The figure also shows RB normalized results, or adjusted speeds which reflect how many resource blocks (RBs) the network assigned the smartphone. RB normalized data speeds adjust for other smartphones in the cell which the network is also assigning RBs. In effect, RB Norm data speeds indicate potential data speeds in an empty network, and they are important to show since we assume today's LTE networks have more commercial traffic than today's 5G networks. They don't, however, take into consideration the impact of higher interference which also exists with network loading, so one could infer that RB Norm data speeds could understate potential data speeds in an empty network.

Figure 3. Median 5G, LTE and Total Throughput – measured and RB normalized



Source: SA 07/03/19: "K-Pop Meets 5G" – Figure 32

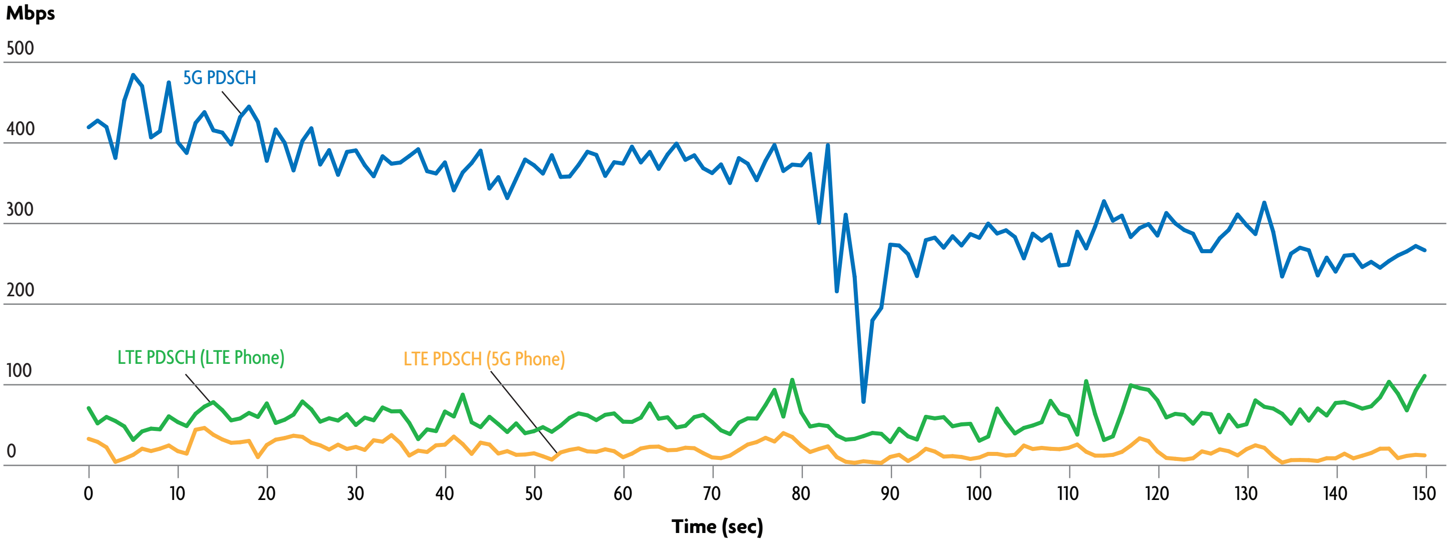
Operators are using EN-DC to make the most out of their overall network while also improving the user experience with higher data speeds and seamless data connectivity.

Figure 3 also highlights an important point about 5G network performance that is largely misunderstood and underappreciated. Operators are using EN-DC (E-UTRA New Radio – Dual Connectivity) with support for split bearer connectivity which allows the mobile device to receive two parallel data streams – one over the LTE network and one over the 5G network. This situation means that the observed data speed on a smartphone, for example, when using a popular speed measurement application, reflects contributions from both networks and not just the 5G network. Although the implication is that true 5G data speeds are frequently being overstated, we believe EN-DC is a very "good thing" since it allows an operator to make the most out of its overall network and it improves the user experience by boosting data speeds and providing seamless data connectivity. When operators deploy 5G in lower frequency bands, EN-DC will evolve to 5G NR carrier aggregation, meaning multiple 5G radio bearers in higher and lower frequencies concurrently serving the same mobile device.

In this case, the LTE network contributed a median data speed of 63 Mbps or 223 Mbps with RB normalization. The individual contributions from 5G (197 Mbps) and LTE (63 Mbps) do not sum up to the total throughput (260 Mbps) since our calculations stem from the entire test. The LG V50 smartphone was periodically connected to LTE without any contribution from 5G, just as the smartphone was connected to the 5G network without any contribution from the LTE network.

Finally, Figure 4 shows a time series plot of the observed data speeds for the two smartphones in one-second time increments. The blue line shows the 5G data speeds for the LG V50 and the Yellow line shows its 4G data speeds. The sum of the two lines (not shown) reflects the total data speed of the phone. The green line illustrates the data speed for the LG G8 smartphone, which only supported LTE.

Figure 4. SK Telecom 5G Walk Test Real-Time Data Speeds



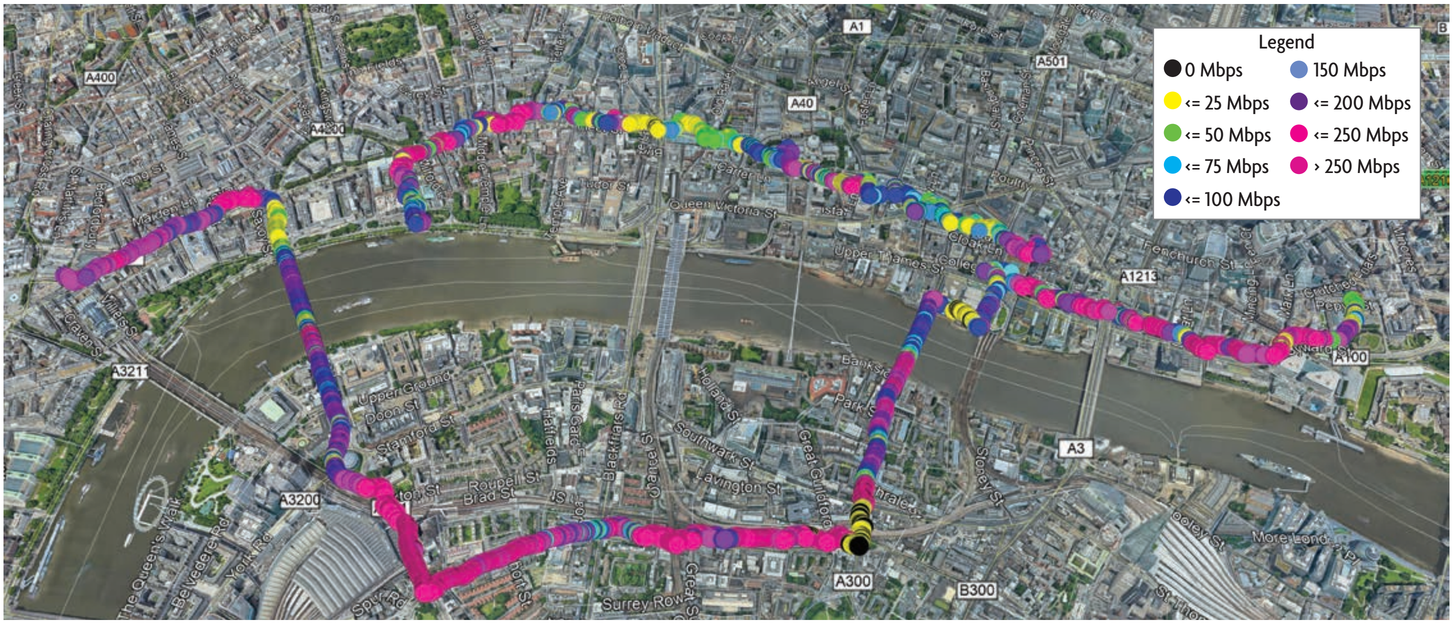
Source: SA 07/03/19: "K-Pop Meets 5G" – Figure 32

We now turn to Europe and EE's 5G network in London. We tested EE's network in mid-August. Based on our analysis of the data, the operator was using 95 MHz of spectrum (5CCA) in addition to 40 MHz of spectrum at 3.5 GHz for its 5G network. Our priority for our European testing was to identify the incremental performance differences between 5G and LTE as they pertained to the user experience. However, we also took the opportunity to characterize overall network performance based on some walk testing and drive testing that we did.

In EE's network in Central London the average data speed was 127.7 Mbps (peak = 600 Mbps) with a data speed of at least 50 Mbps for 76% of the time.

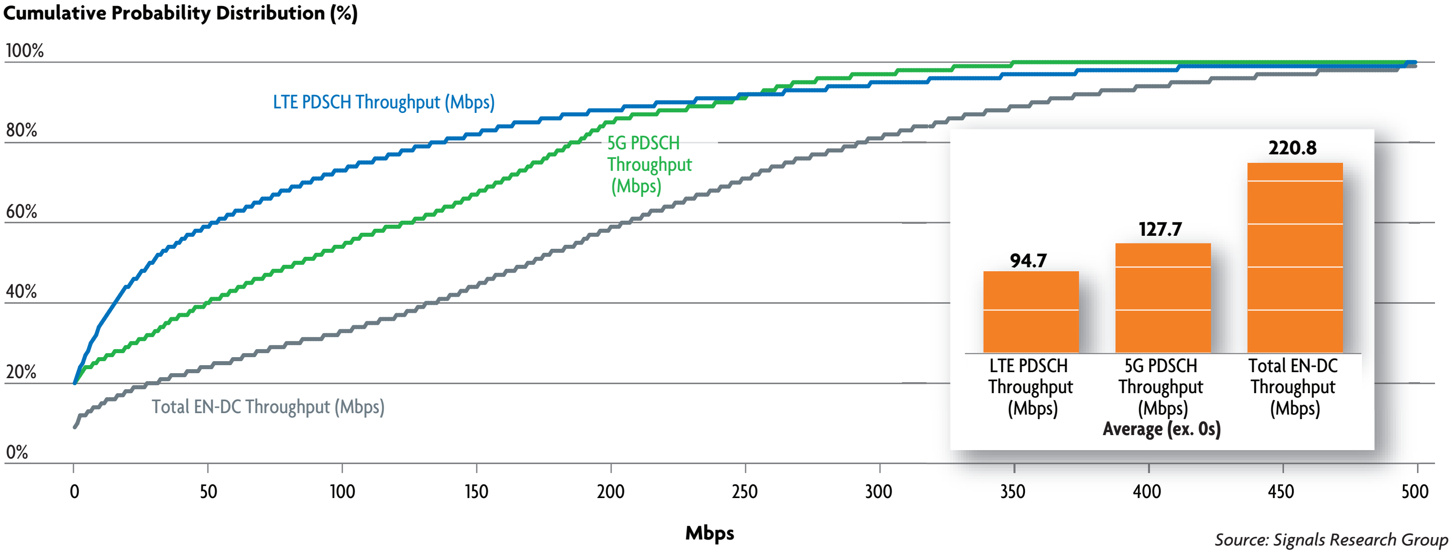
Figure 5 provides a geo plot of a 6.75 kilometer walk test that we did in central London during the mid-morning hours. During the walk, we downloaded approximately 135 GB with a OnePlus 7 Pro smartphone using popular applications, such as Google Drive and Netflix, running in parallel. As shown in Figure 5, the average data speed was 220.8 Mbps with the 5G network contributing an average data speed of 127.7 Mbps. Put another way, the data speed was at least 50 Mbps for 76% of the time with a peak physical layer data speed of approximately 600 Mbps (not shown). Since the smartphone wasn't always using 5G (or 5G with LTE), there were instances when one of the radio bearers wasn't contributing to the total throughput. This information is evident in the distribution figure by observing the start of the curves at 0 Mbps.

Figure 5. Central London Walk Test



Source: Signals Research Group

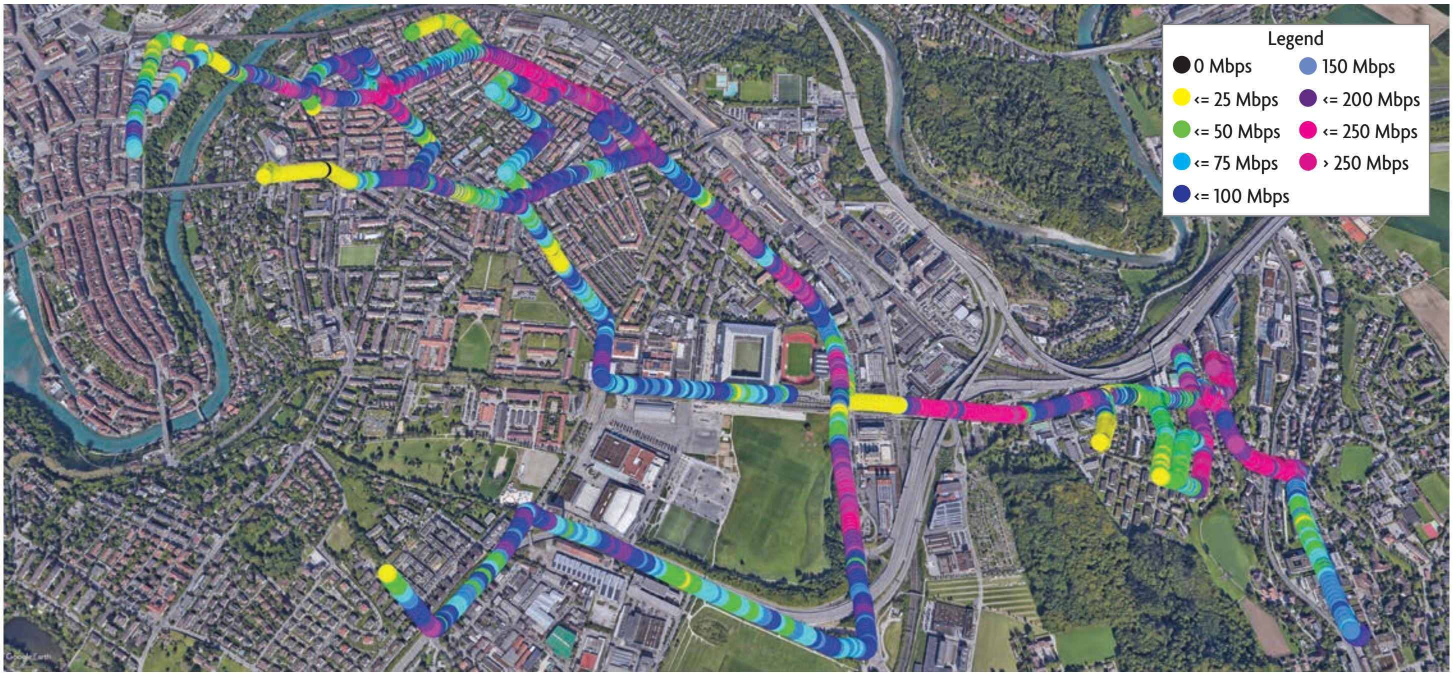
Figure 6. Distribution of EN-DC Data Speeds – EE Network in Central London



Source: Signals Research Group

We now head south to Bern Switzerland where Swisscom has deployed 100 MHz of 5G at 3.5 GHz along with its legacy LTE network, which we found included 70 MHz of FDD spectrum supporting 4CCA in the areas where we tested. Although most of our testing was done close to the train station, we took the opportunity to rent a car and drive around the city on the last morning of our visit. Figure 7 provides a geo plot of the measured data speeds with the OPPO Reno 5G smartphone. Although it isn't evident in the figure, we also had a second smartphone that we locked to LTE. The implication is that the total data speeds showed in the figure understate the potential contribution from LTE since

Figure 7. Geo Plot of EN-DC Data Speeds – Swisscom network in Bern, Switzerland



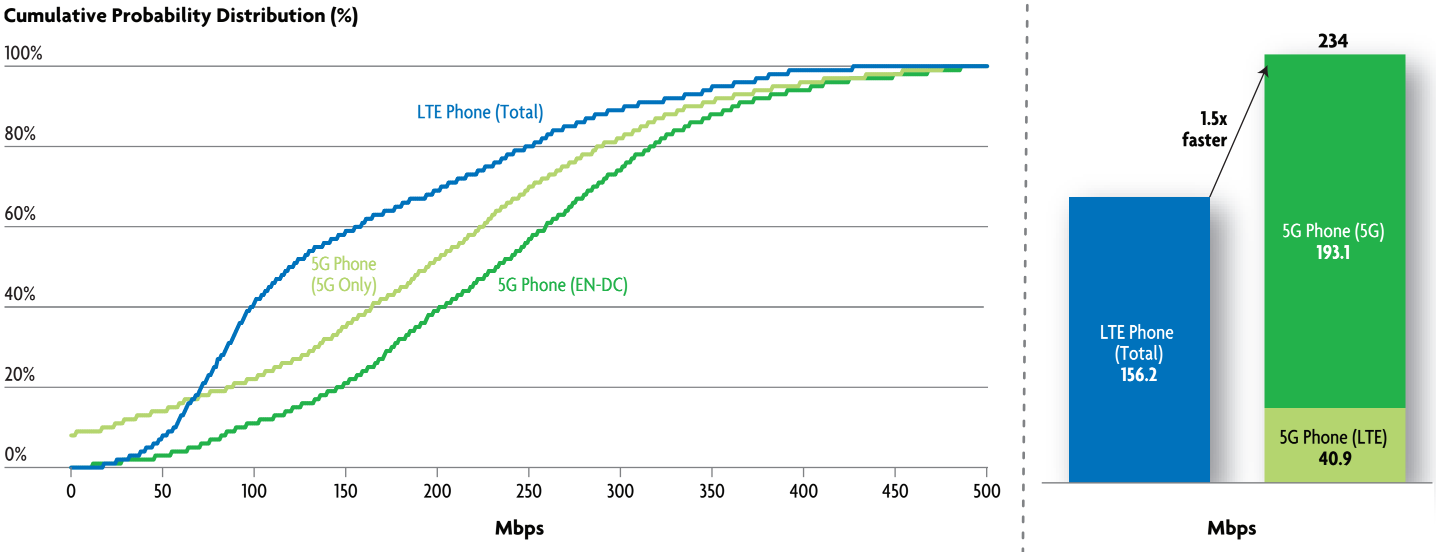
Source: Signals Research Group

we had a second LTE smartphone consuming full buffer data transfers at the same time we were testing with the 5G smartphone.

In Swisscom's network, the OPPO Reno 5G smartphone was 1.5x faster than the LTE-Only smartphone in a series of drive tests involving the transfer of more than 76 GB of data.

Figure 8 shows a distribution plot of the data speeds for the 5G smartphone and the LTE-Only smartphone for those periods when the 5G smartphone was attached to the 5G network. For the OPPO Reno 5G smartphone the figure shows the individual contributions of 5G and LTE to its total throughput. In this series of tests, the two smartphones downloaded more than 76 GB of data with the 5G smartphone achieving 1.5x higher data speeds.

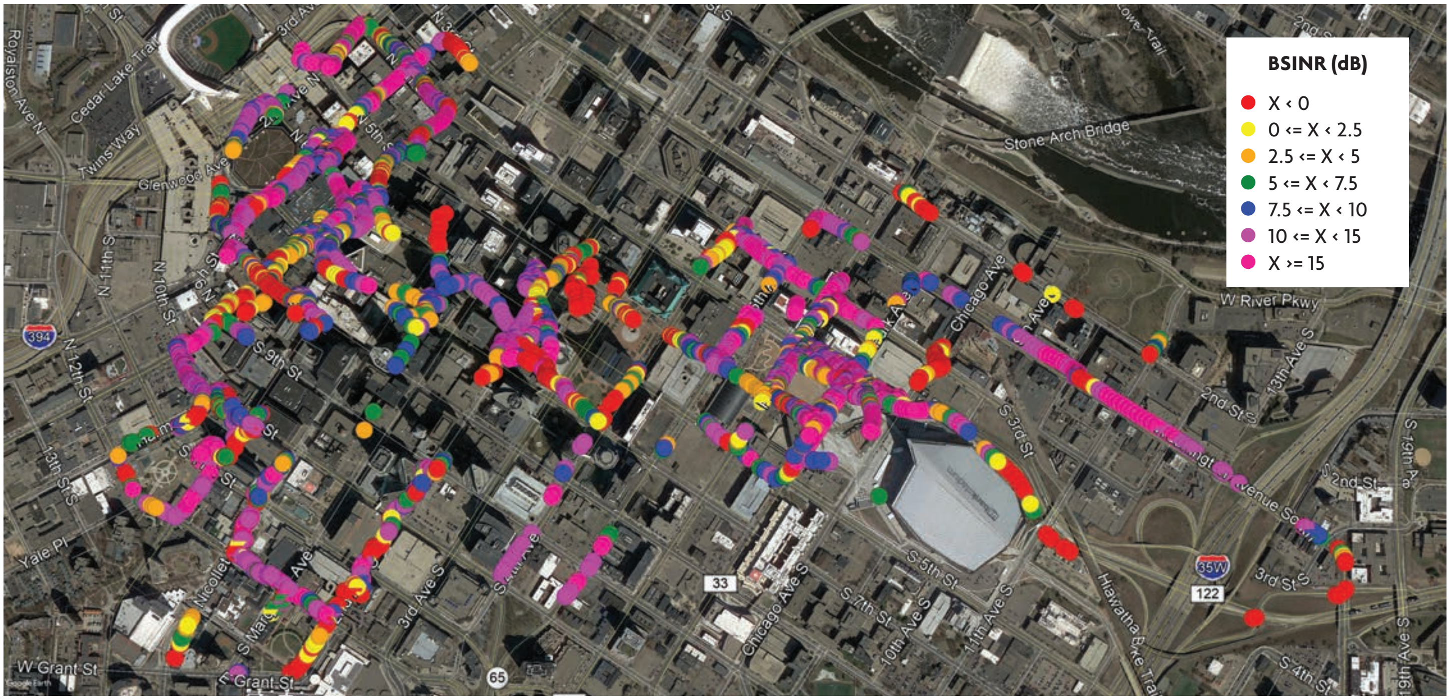
Figure 8. Distribution of EN-DC Data Speeds – Swisscom Network in Bern, Switzerland



Source: Signals Research Group

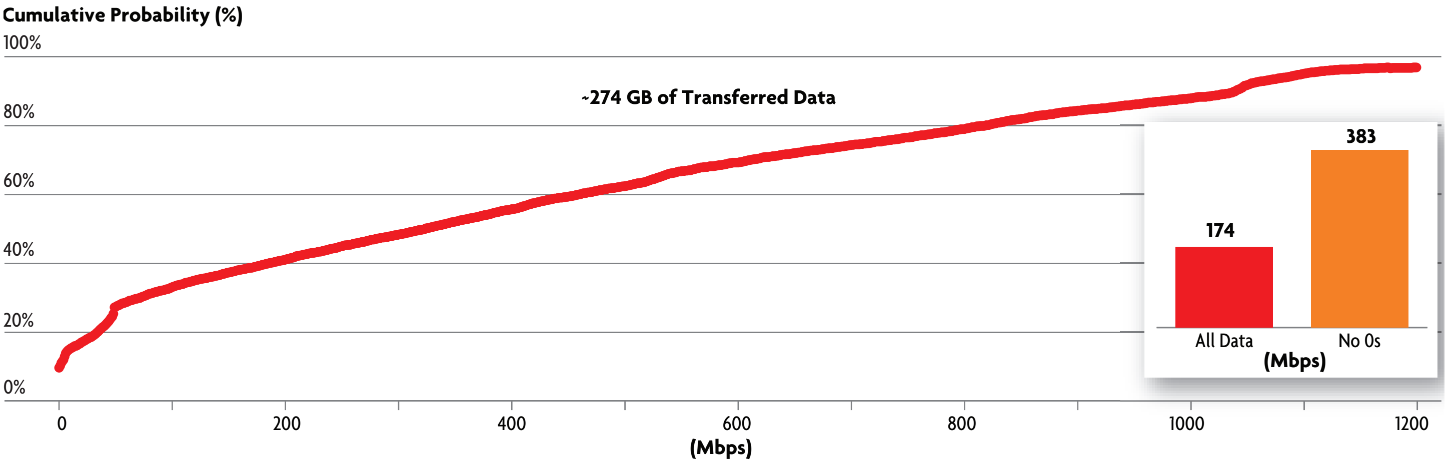
Finally, we return to our neck of the woods and the Verizon Wireless 5G network (400 MHz of spectrum @ 28 GHz) in downtown Minneapolis. Figure 9 illustrates the signal quality (BSINR) of the 5G millimeter wave signal, as observed by the Motorola Moto Z3 smartphone with the 5G moto mod. Signal quality and signal strength, in our view, are a better indicator of network performance since these parameters exclude extraneous factors which can influence data speeds, and which do not reflect the full capabilities of the network. To put things into perspective, higher BSINR results in faster data speeds, although data speeds of several hundred Mbps are possible with a BSINR of only a few dB. Gigabit data speeds generally require a BSINR closer to 10 dB or higher – much also depends on the channel bandwidth of the 5G transmission.

Figure 9. Geo Plot of 5G Millimeter Wave Signal Quality – Verizon Wireless network in Minneapolis, MN



Source: SA 05/06/19: "Vikings vs. Bears" – Figure 13

Figure 10. 5G PDSCH Throughput Distribution Plot – Verizon Wireless network in Minneapolis, MN



Source: SA 05/06/19: "Vikings vs. Bears" – Figure 4

As shown in Figure 10, we observed a median 5G data speed of 383 Mbps when the smartphone was attached to the 5G network and receiving data, as well as peak speeds approaching 1.5-1.6 Gbps. At the time we tested the network, immediately after the operator launched commercial services in April, the operator was not using EN-DC with split bearer functionality to boost data speeds with the LTE network. However, as we'll show in the next section, the smartphone moved relatively seamlessly between the two networks when moving in and out of 5G coverage.

Verizon's 5G deployment has also resulted in a big performance boost to its LTE network.

It is worth mentioning that Verizon's 5G deployment has also resulted in a big performance boost to its LTE network. We attribute the gain to the operators use of small cells – most 5G cell sites are collocated with LTE small cells on light poles in the city. In our testing we observed median data speeds of 89.5 Mbps on the LTE network, or 116.1 Mbps with RB normalization – substantially higher than the typical data speeds that frequently get reported. We return to 5G millimeter wave in the next two sections of the paper.

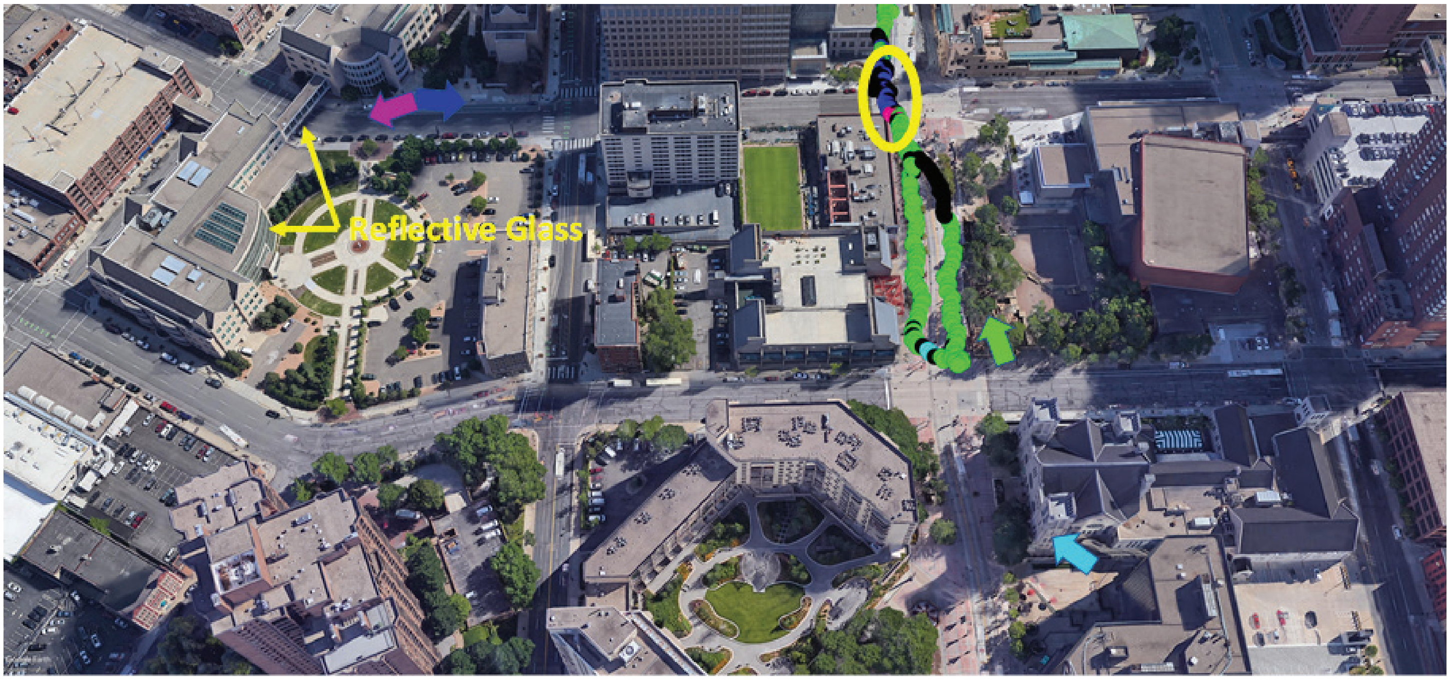
5G Millimeter Wave Signals are More Resilient than Generally Perceived with Additional Performance Gains Coming

When it comes to misunderstandings and false impressions, nothing comes close to 5G and how it performs in millimeter wave frequencies. Without question, the behavior of a millimeter wave signal is "unique," and it requires a paradigm shift in thinking about cellular networks and how they are deployed. Furthermore, we know from lots of experience that it isn't possible to understand how millimeter wave works by using a simplistic speed measurement application on a smartphone.

The best way to illustrate the potential of millimeter wave is to view geo plots of millimeter wave coverage from adjacent cell sites, as well as the coverage from individual beams from a single 5G cell site. Unlike traditional cellular radios, a 5G radio operating in a millimeter wave frequency band uses discrete beams to target RF energy in a specific direction. These targeted beams – akin to a laser beam versus a light bulb – are crucial to 5G millimeter wave performance since they help overcome some of the propagation challenges that exist with the higher frequency band. These targeted beams also account for some very interesting characteristics that we will now demonstrate.

We first highlighted these characteristics in our May *Signals Ahead* report. We have since recreated many of the original figures used in that report to provide better clarity into the characteristics that we want to highlight. Figure 11 provides a geo plot of 5G millimeter wave coverage in downtown Minneapolis along Nicollet Mall. Each colored arrow represents the location of a 5G radio, as well as the direction the radio is facing. Each colored circle identifies the 5G radio (cell PCI value) that the Motorola smartphone was attached to at that point in the walk. To reduce the complexity, we've excluded 5G cell sites and radios which are not pertinent to the analysis. By our count, there are three additional 5G cell sites and eight 5G radios not shown in the figure – each 5G site has two 5G radios pointing in different directions. Although less important to the analysis, we note that the block where we walked was the site of major festivities when Minneapolis hosted the recent Super

Figure 11. Geo Plot of 5G Millimeter Wave Coverage along Nicollet Mall



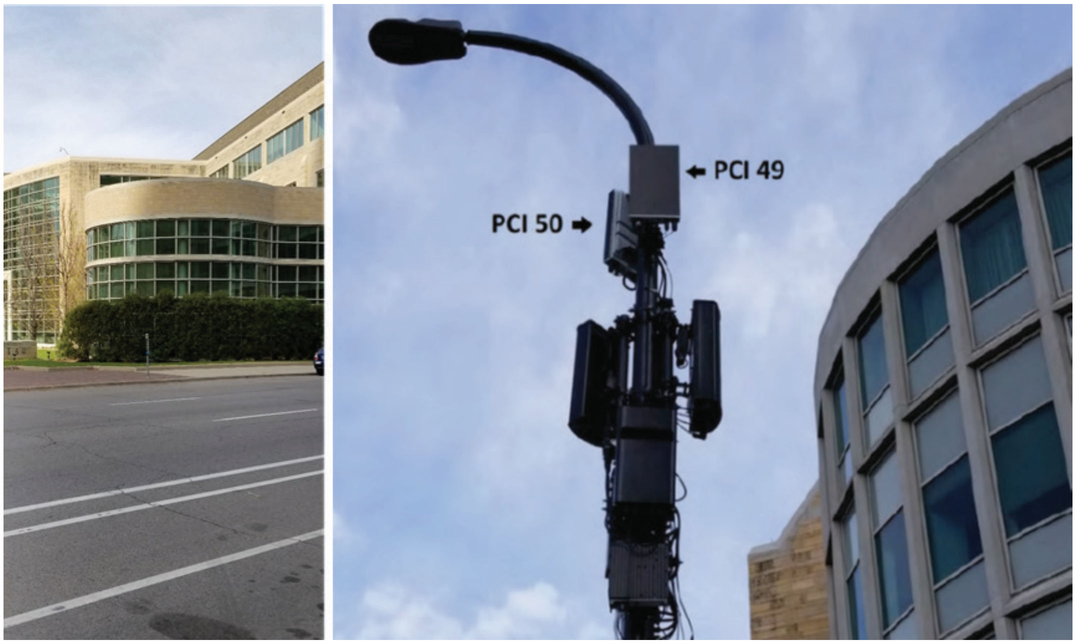
Source: recreated from SA 05/06/19, "Vikings vs. Bears" – Figure 29

Bowl and NCAA Final Four basketball tournament. We stood on this block along with hundreds of other people watching Virginia beat Auburn with some clutch free throws just days before doing our first tests in this area. We've returned multiple times since our first test to replicate the results that we first observed.

The figure shows that our smartphone connected to four different 5G radios during the one-block walk, even though we were walking toward a radio that was directly facing us (the green arrow, or PCI 229). When we were perpendicular to the direction the PCI 229 5G radio was facing and just outside of the 5G radio's transmission the phone briefly handed off to PCI 227 (Cyan arrow), even though the 5G radio is largely out of view from this location. On the return trip back to the start location at the intersection of Nicollet Mall and 11th Avenue, the Motorola smartphone switched to PCI 50 (Magenta arrow and circles) and then PCI 49 (Dark Blue arrow and circles), or the two radios collocated 1.5 blocks to the west (directionally left in the figure).

The truly remarkable aspect of this observation is that the 5G radio associated with PCI 50 was facing nearly the opposite direction from the intersection of 11th Avenue and Nicollet Mall. Figure 12 shows a picture of the lamppost with the two 5G radios. We took this picture while standing on 11th Avenue between the lamppost and Nicollet Mall. Although it isn't crystal clear in the figure, we are certain there is no way the PCI 50 radio could have transmitted a signal directly to the intersection (signals don't radiate out of the back plate of the radio), meaning the signal had to have reflected off a building and then reached the smartphone at the Nicollet Mall intersection. The second image in Figure 12 shows the building directly in front of the PCI 50 5G radio and the likely source of the reflection. There is also an enclosed glass skyway crossing 11th Avenue which could have been the source of the reflection. Note that the building and the skyway are close to two blocks away from the intersection, as previously shown in Figure 11.

Figure 12. 5G Cell Site Along 11th Avenue



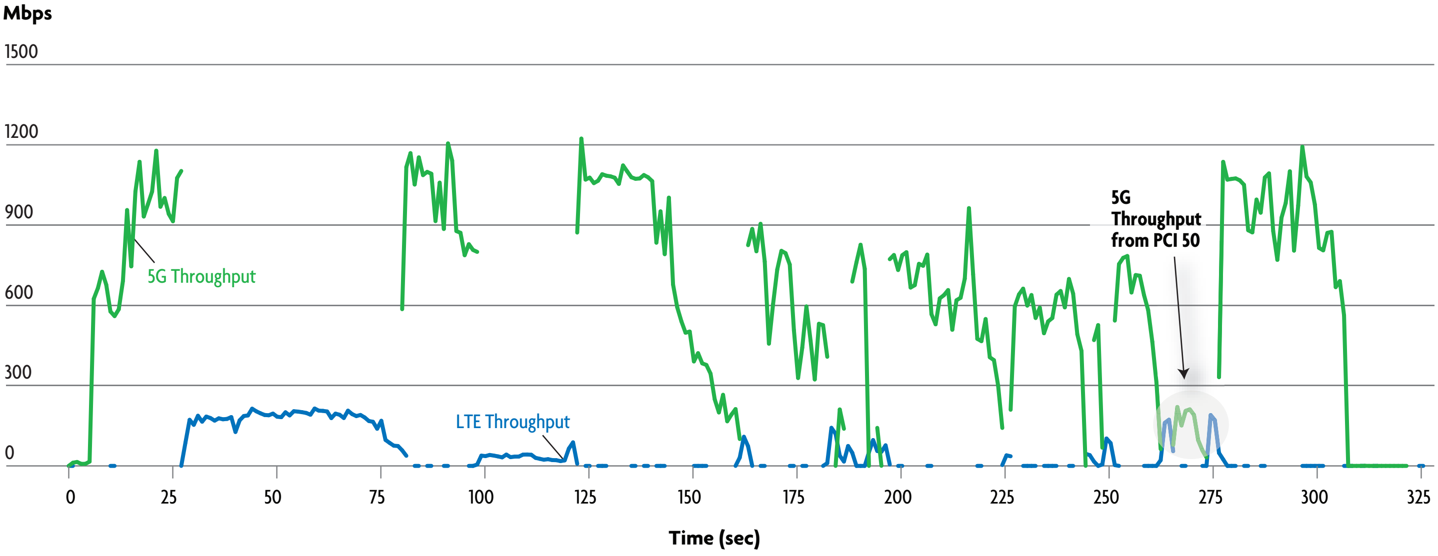
Source: recreated from SA 05/06/19, "Vikings vs. Bears" – Figure 29

A reflected millimeter wave signal from nearly two blocks away delivered a data speed of approximately 200 Mbps.

In addition to attaching to PCI 50, the Motorola smartphone achieved meaningful throughput while connected to it, as shown in Figure 13. This figure shows a time series plot of the measured 5G and LTE data speeds on the out and back walk. The highlighted region around 270 seconds indicates the period when the smartphone was attached to PCI 50 – the contribution from PCI 49 follows for the duration of the test. Although the data speeds with PCI 50 were not the heralded 5G data speeds that are possible with millimeter wave, we find it very impressive to observe speeds of approximately 200 Mbps with a reflected millimeter wave signal from nearly two blocks away.

Figure 13, along with Figure 14, highlights another very important observation and a key reason why casual 5G testers frequently mischaracterize millimeter wave performance. Figure 13 shows several instances when there wasn't 5G connectivity and the smartphone used the LTE network instead. In Figure 11 these areas are highlighted by the black circles. The LTE data speeds appear low, but that is largely because the 5G data speeds were very good. In many cases the LTE data speeds hovered near 200 Mbps. A casual observer testing in this area might conclude that millimeter wave propagation challenges were to blame for the lost 5G connection – we note there is a tree that partially obscures the directional path of the PCI 229 5G radio pointing down Nicollet Mall. However, as shown in Figure 14 the 5G signal strength (BRSRP) was quite strong each time the smartphone lost the connection and then immediately after reconnecting to the 5G radio bearer.

Figure 13. 5G and LTE Throughput



Source: recreated from SA 05/06/19, "Vikings vs. Bears" – Figure 31

What is also clear in the figure is that the smartphone handed off to a new LTE cell site (PCI) each time it lost/regained the 5G connection. In Figure 14, the horizontal blue lines show the LTE PCI value (primary Y axis) and the green line shows the 5G signal strength (BRSRP) plotted along the secondary Y axis. As shown in the figure, the smartphone connected to five different LTE PCI values during this short walk, in addition to the four different 5G PCIs, located at three different cell sites.

Generally, changes in the LTE PCI don't have an impact on 5G connectivity. However, with the NSA (non-standalone) architecture that operators are using today there is an important dependency between the two networks. If an LTE cell site isn't aware of the nearby 5G radio, the scheduler won't leverage it to simultaneously transmit data to the attached smartphone. Operators map the most likely pairings of LTE and 5G cell sites, but they don't always identify every single possible permutation. An LTE signal from a cell site can extend into a region where it isn't expected and when this situation occurs the mapping of LTE and 5G cell sites doesn't reflect what is happening in the network. We've seen this situation in all networks that we've tested (sub 7.125 GHz and millimeter wave) and it largely explains why our LG V50 smartphone in Seoul wasn't always attached to the 5G network.

Figure 14. 5G Signal Strength and Changes in the LTE Anchor Cell

Source: recreated from SA 05/06/19, "Vikings vs. Bears" – Figure 28

We conclude our discussion of the Verizon Wireless 5G network in Minneapolis by showing another example in which the 5G radio provided coverage with non-line-of-site conditions. Figure 15 shows a picture of a 5G cell site with two radios (we highlighted another site in the background), including one radio (PCI 99) that was at a 45-degree angle to the street and pointing into the third-floor window of a five-story building. Setting aside the unconventional placement of the radio, the transmitted signals provided very good coverage along the street alongside the lamppost as well as the street which runs perpendicular to it. In the figure, we grouped the BRSRP into three categories. Green reflects very good signal strength (BRSRP > -105 dBm), yellow indicates decent signal strength (BRSRP > -110 dBm) and red indicates marginal signal strength (BRSRP < -110 dBm). We point that a smartphone can connect to a 5G millimeter wave signal with BRSRP below -110 dBm but the performance is not reliable. Nonetheless, having studied this area in detail and scrutinized the direction the PCI 99 5G radio was facing, we conclude the signal had to have reflected off the building, perhaps multiple buildings, in order to reach around the corner.

Figure 15. PCI 99 5G Radio

Source: SA 05/06/19, "Vikings vs. Bears" –Figure 72

Figure 16. Signal Strength with NLOS Radio Conditions

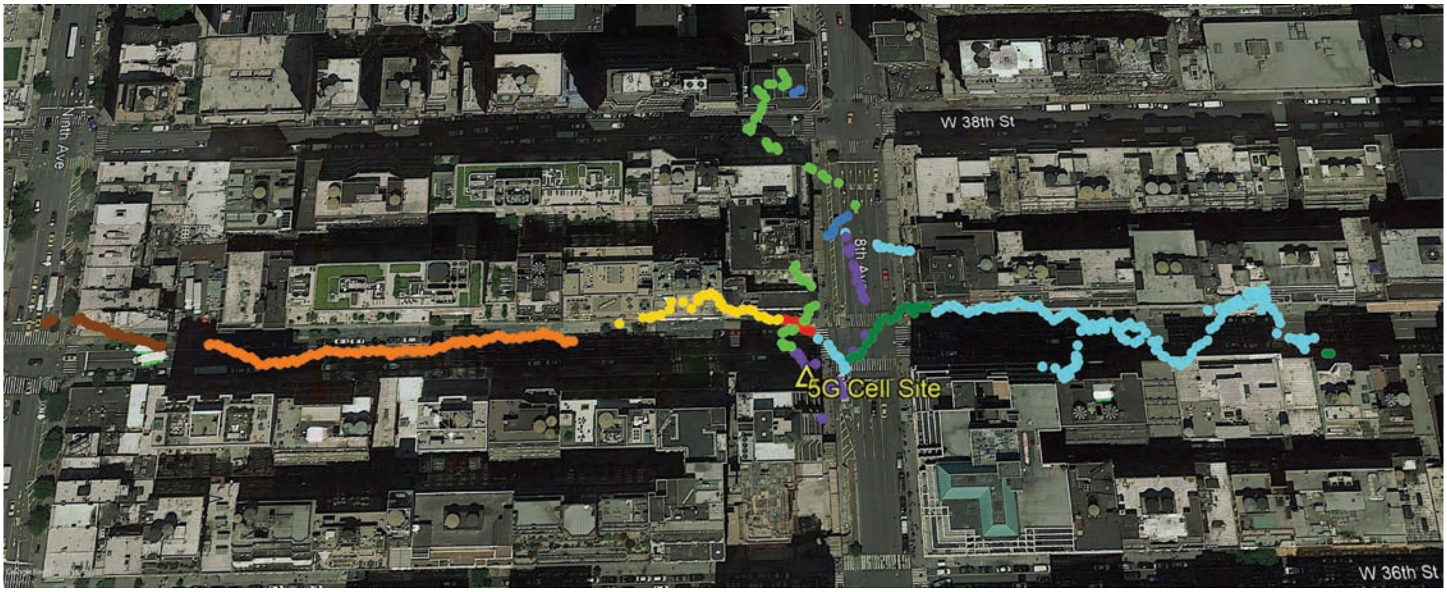
Source: recreated from SA 05/06/19, "Vikings vs. Bears" – Figure 37

T-Mobile USA has launched 5G millimeter wave (28 GHz) with a 100 MHz radio channel in multiple markets, including New York City. We tested that market in August and we are including a couple of figures in this paper from that study. We previously mentioned how 5G radios use targeted beams to direct the RF energy with millimeter wave frequencies to improve the propagation characteristics of the 5G signal.

From a single location it is possible to direct 5G coverage in more than one direction along city streets.

Figure 17 provides a geo plot of each unique beam index from two co-located 5G radios that the operator had deployed at a legacy LTE site (Figure 18). Each unique beam index is based on what the Samsung Galaxy S10 smartphone used when we tested in this area. We used autumn colors, including red, to indicate unique beams coming from one 5G radio (the radio shown on the right in Figure 18). The remaining colors – the blues, greens and purples – illustrate different beam indices from the second 5G radio. The interesting observation is that from a single location it is possible to direct 5G coverage in more than one direction along city streets.

Figure 17. 5G Beam Indices from Two 5G Radios



Source: SA 08/19/19, "Strange Bedfellows" – Figure 34

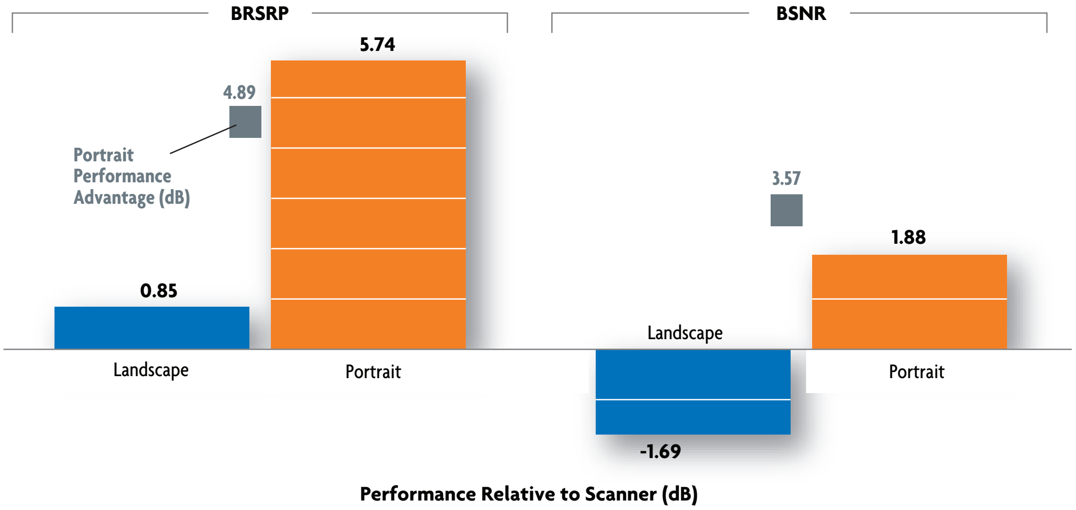
Figure 18. T-Mobile USA 5G Cell Site

Source: SA 08/19/19, "Strange Bedfellows" – Figure 33

5G millimeter wave smartphones can also use different beam indices, based on how they are being held. We've done several tests in the last several months to characterize potential performance differences associated with holding the smartphone in portrait mode versus in landscape mode (commonly used when watching videos). In our most recent tests, we used a PCTEL scanner to independently characterize the strength and quality of the 5G millimeter wave signals while walking with a Galaxy S10 smartphone being held in in portrait or landscape mode. We repeated the test with each position while walking along the same street in downtown Minneapolis.

Figure 19 shows the results from this study. The vertical bars represent the difference in dBs between the reported signal strength/quality when holding the Galaxy S10 in landscape and portrait modes relative to the neutral scanner, which we carried in a backpack during the tests. In this study and with this smartphone, we found that holding the phone in portrait mode resulted in better signal strength (4.89 dB better) and improved signal quality (3.57 dB higher). These results could vary based on where the handset vendor places the antenna modules on the smartphone.

Figure 19. The Impact of Device Placement on Signal Quality and Signal Strength



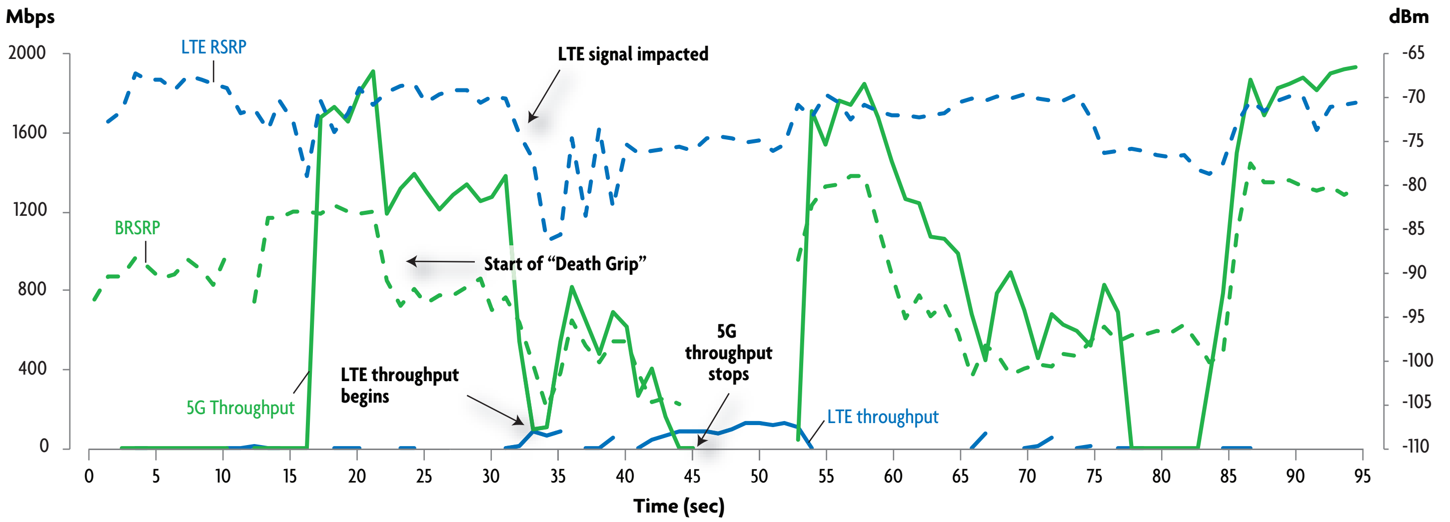
Source: recreated from SA 05/06/19, "Vikings vs. Bears" – Figure 28

It takes two hands squeezing tightly on the back of a smartphone to have a major impact on the 5G connectivity.

We've also analyzed hand placement on the smartphone and its impact on performance – signal strength, signal quality and data speeds. The information provided in Figure 20 shows typical results that we've observed in our studies. The figure provides a time series plot of data speed and signal strength during the test. With two hands placed on the backside of the smartphone there can be some minor degradation to performance. However, it takes two hands fully covering the smartphone and squeezing tightly to have a major impact – with considerable effort it is possible for the smartphone to lose the 5G connection at which point it reverts to LTE. Note that our "death grip" also impacted the LTE performance as reflected in the drop in the LTE signal strength (the dashed blue line). In this figure, the drop in the 5G throughput at ~78 seconds stems from the completion of the data session, hence we believe focusing on the 5G signal strength (the dashed green line) is more appropriate.

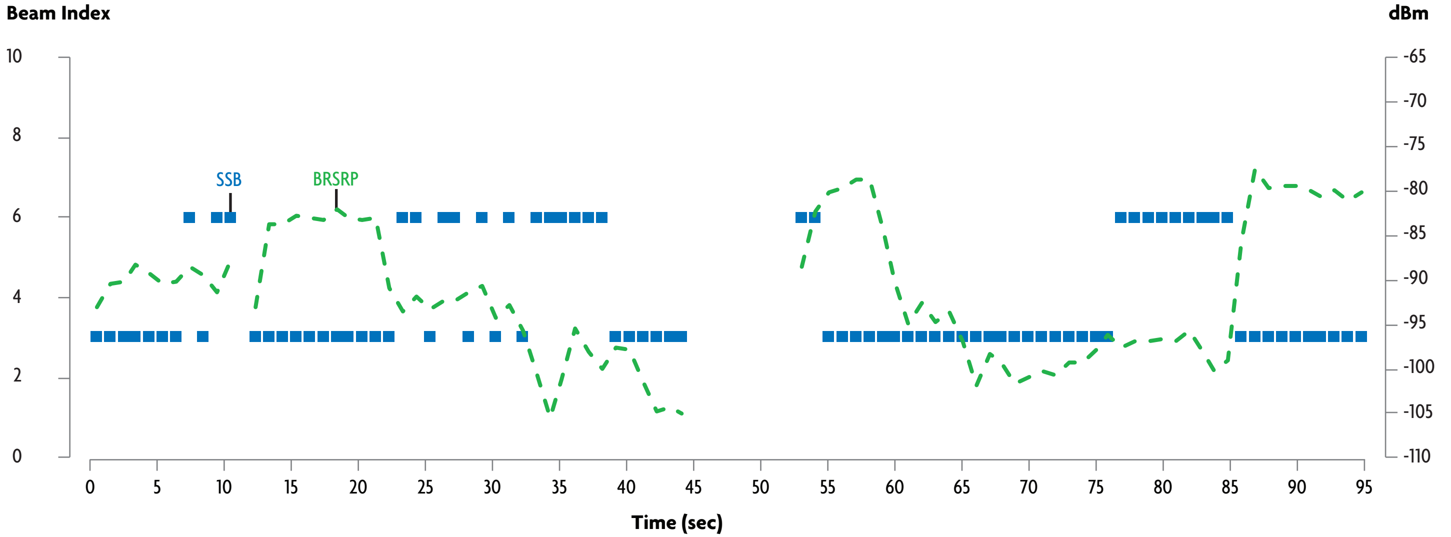
We've also observed smartphones using different beam indices due to hand placement, even while standing in the same physical location. An example of this phenomenon is provided in Figure 21. Note how the death grip caused the phone to switch back and forth between Beam Index 3 and Beam Index 6. Normally, a smartphone will retain the same beam index from a fixed location and then change beam indices as it moves throughout the cell coverage area.

Figure 20. The Impact of the "Death Grip" on Throughput and Signal Strength



Source: Signals Research Group

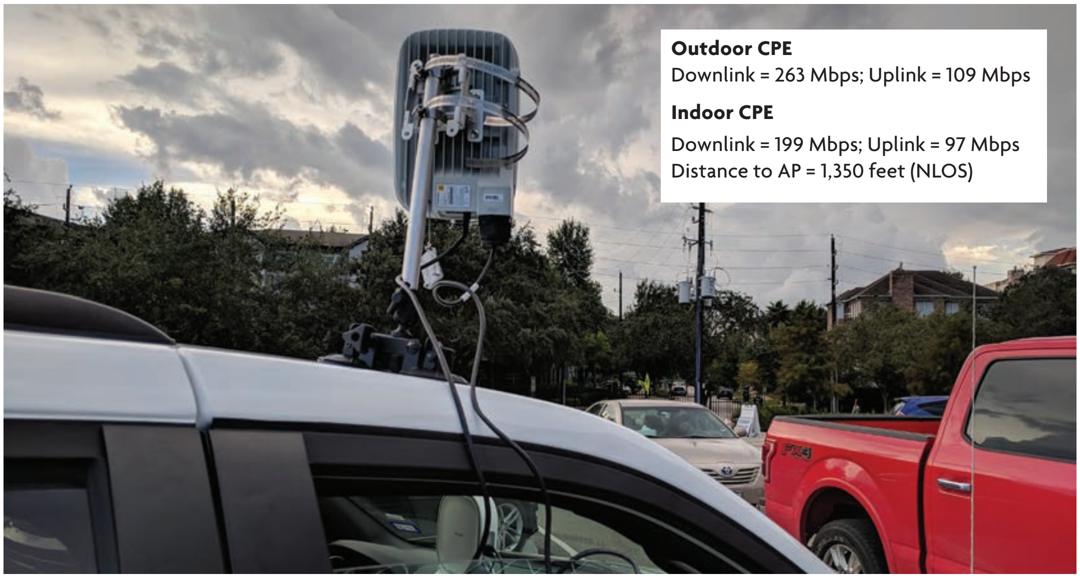
Figure 21. The impact of the "Death Grip" on Beam Index Selection



Source: Signals Research Group

Finally, we revisit Verizon's fixed wireless network to illustrate why we believe the potential for millimeter wave coverage is very promising. Although Verizon used its own 5GTF standard when it first deployed fixed wireless coverage, we believe the propagation characteristics of the 5GTF standard are very comparable to what is observed with the 3GPP standard – both solutions use 28 GHz. In our testing of the fixed wireless network in Houston, Texas, we observed 5G connections with meaningful data speeds in areas of the network where no one would have expected it to work. In addition to connecting to a 5G radio hidden behind homes and buildings, we observed 5G connectivity at great distances, as shown in Figure 22. In this case, the 5G radio was approximately 1,350 feet (0.4 kilometers) away from our test location. More importantly, the radio, which was mounted to a utility pole, was hidden from view behind the apartment buildings shown in the figure. Nonetheless we observed good data speeds with both an indoor and outdoor CPE.

Figure 22. Extended Millimeter Wave Coverage with Fixed Wireless



Outdoor CPE
Downlink = 263 Mbps; Uplink = 109 Mbps

Indoor CPE
Downlink = 199 Mbps; Uplink = 97 Mbps
Distance to AP = 1,350 feet (NLOS)

Source: SA 10/22/18 "Catching the Wave" – Figure 14

We attribute the extended coverage of the fixed wireless network to the uplink transmit power of the CPEs.

Verizon was using 600 MHz for the 5G fixed wireless network compared with the 400 MHz that we observed in Minneapolis and Chicago. However, the wider channel bandwidth doesn't explain the RF connectivity. Instead, we attribute the extended coverage to the uplink transmit power of the CPEs. Both the indoor and outdoor CPEs transmitted at 33 dBm compared with the ~23 dBm that we observed with the 5G smartphones that we've used in our testing. Due to regulatory restrictions, we'll never see a 5G millimeter wave smartphone transmit at 33 dBm. However, there is a forthcoming feature of 5G that is key to extending the performance and coverage of 5G millimeter networks.

Moving uplink control channel information to a lower frequency band will meaningfully improve the coverage and capacity of today's 5G millimeter wave networks.

Once vendors have introduced the ability to deploy 5G in lower frequency bands they will be able to use the lower bands to transmit the uplink control channel information (ACKs, NACKs, etc.) that are currently carried over the millimeter wave spectrum. Moving to the lower frequency band is arguably better than increasing the transmit power when it comes to extending coverage. Furthermore, by moving the uplink control channel information to a lower/different frequency band, an operator will be able to dedicate the millimeter wave spectrum to downlink transmissions. Today, they must reserve a portion of the spectrum (in time) to uplink transmissions. Once operators take this step, they will have additional downlink capacity in their millimeter wave bands and they'll have the ability to deliver even higher data speeds.

Indoor Deployments of 5G Millimeter Wave are Already Occurring with Favorable Results

After watching a Verizon Wireless 5G commercial touting its 5G coverage in thirteen NFL stadiums across the United States, we reached out to the local office to see if its coverage in US Bank Stadium, home to the Minnesota Vikings, was real and if it warranted our testing of the coverage. Verizon invited us to test the stadium for a day and gave us unlimited access throughout the stadium. Side note – getting into US Bank Stadium is much harder than getting into the US Capital. Although we haven't completed our analysis of the data – we have looked at most of it – we can share some snippets of information in this paper. Figure 23 shows a 5G cell site outside of US Bank Stadium – we took this picture back in April 2019 when we first tested the network. Figure 24 shows a picture of two 5G radios mounted along the catwalk in US Bank Stadium. In total, Verizon has 12 5G radios serving the inside seating area the stadium and another radio inside the stadium located near Verizon Gate where the operator has an activation site that it uses on game day to promote its network.

Figure 23. Outside US Bank Stadium – April 2019

Source: Signals Research Group

Figure 24. Inside US Bank Stadium – October 2019

Source: Signals Research Group

Over the course of a day, we walked the entire stadium, walking through up to 3 rows in each section on all levels, including the end zone sections. In addition to measuring the signal strength and quality with Galaxy S10 smartphones we performed various tests (downlink and latency) to measure network performance to the Umetrix data servers that we had at our disposal. Although we can't definitively state that every single seat in the 66,655-seat stadium has 5G coverage, we are confident that virtually all seats have good, if not great, 5G RF connectivity.

Figure 25 shows the measured BRSRP (signal strength) during some of the tests that we did in the stadium. The signal strength rarely dropped below -100 dBm and frequently it was better than -80 dBm. These results are unheard of in an outdoor 5G millimeter network. On occasion, the smartphone did switch to LTE – we assume during a 5G cell or beam index handover – but the smartphone returned to 5G. We'll know more when we analyze the data in more detail. We note we were walking quickly through the rows while a typical 5G consumer would be stationary – sitting in his or her seat. This observation doesn't suggest that 5G doesn't support mobility since it clearly does. We just want to emphasize that our testing in the stadium didn't fully reflect how a consumer would use his or her smartphone when attending a Vikings football game.

Figure 25. Measured 5G Signal Strength

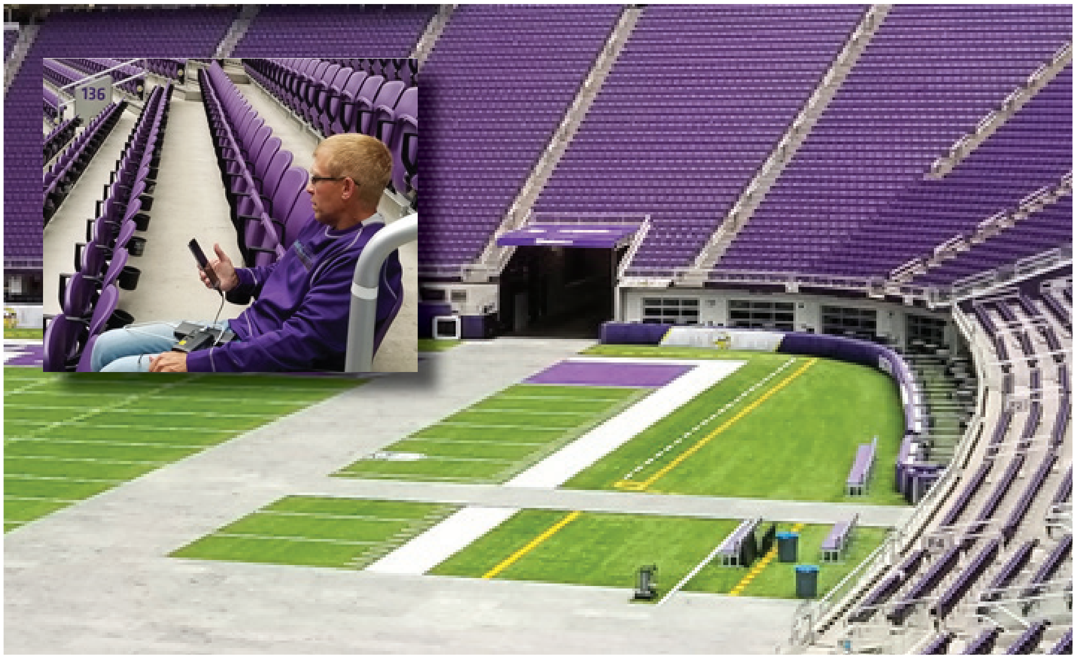
Source: Signals Research Group

When measuring data speeds, we also took the opportunity to evaluate the impact of the underlying protocol (TCP) used to deliver the data packets. With the Umetrix data platform we could set the number of parallel threads used by the server to send the data to the smartphone. Our motivation for doing this series of tests was to demonstrate that the full potential of a 5G network also hinges on the Internet itself, including the capabilities and locations of the data servers and the applications that are hosted on these servers. Speedtest.net, for example, is frequently collocated on a server at an operator's gateway within its data center and it uses multiple concurrent TCP threads when calculating the potential data speed. This methodology is completely fine if the user understands what the results mean. However, these results shouldn't be extrapolated to conclude that a server well outside of the operator's network can deliver the same throughput when downloading an application or other content. We provide user experience results in the next section.

We performed three downlink measurement tests using a Umetrix data server located outside of the operator's network (in Virginia), or a location that is more representative of where a server might be located relative to the access network. In the first 60-sec test we used two concurrent TCP streams, in the second test we used six concurrent TCP streams, and in the last test we used twelve TCP streams.

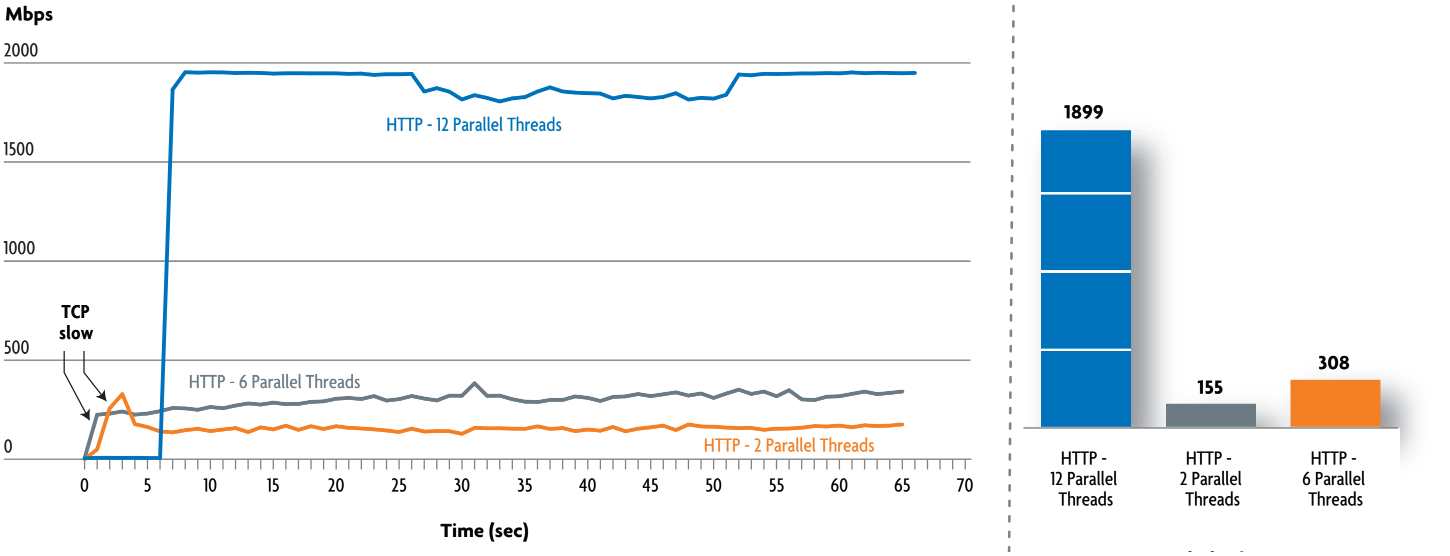
As expected, the throughput with twelve concurrent TCP streams was the highest. Furthermore, the relative speeds compared with the other two scenarios was substantial, as shown in Figure 27. We don't know how many TCP threads popular application servers use when transmitting large files to subscribers, and our point isn't to call out individual services for not optimizing their content delivery mechanisms. However, it is important to observe that the observed data speed in a high bandwidth 5G network hinges on factors other than signal quality, signal strength, and the number of other active users in the network.

Figure 26. Our View While Performing Speed Tests



Source: Signals Research Group

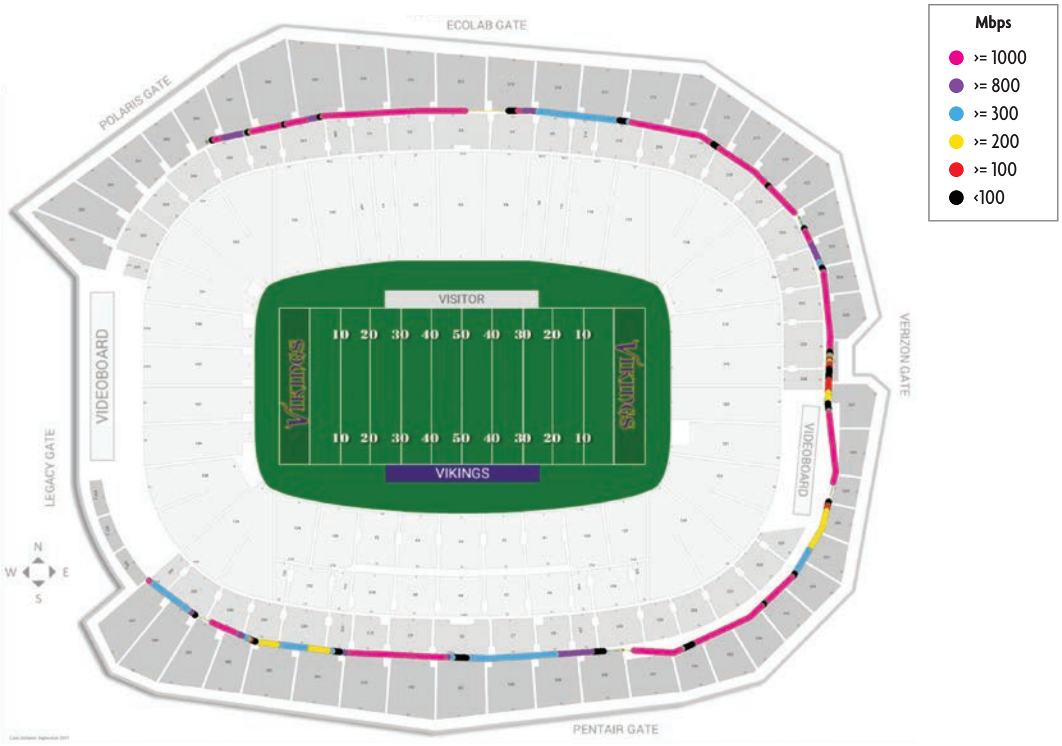
Figure 27. Our Results While Performing Speed Tests



Source: Signals Research Group

In the last figure shown in this section, we show the application layer throughput that we observed while walking behind the stadium seating and where rabid Vikings fans purchase their brats and beer. These results are impressive because the network wasn't designed to provide coverage in this area. However, the RF energy from the 5G radios was able to radiate through the narrow gaps in the stadium seats and find its way into the concourse.

Figure 28. Application Layer Throughput in the US Bank Stadium Concourse



Source: Signals Research Group

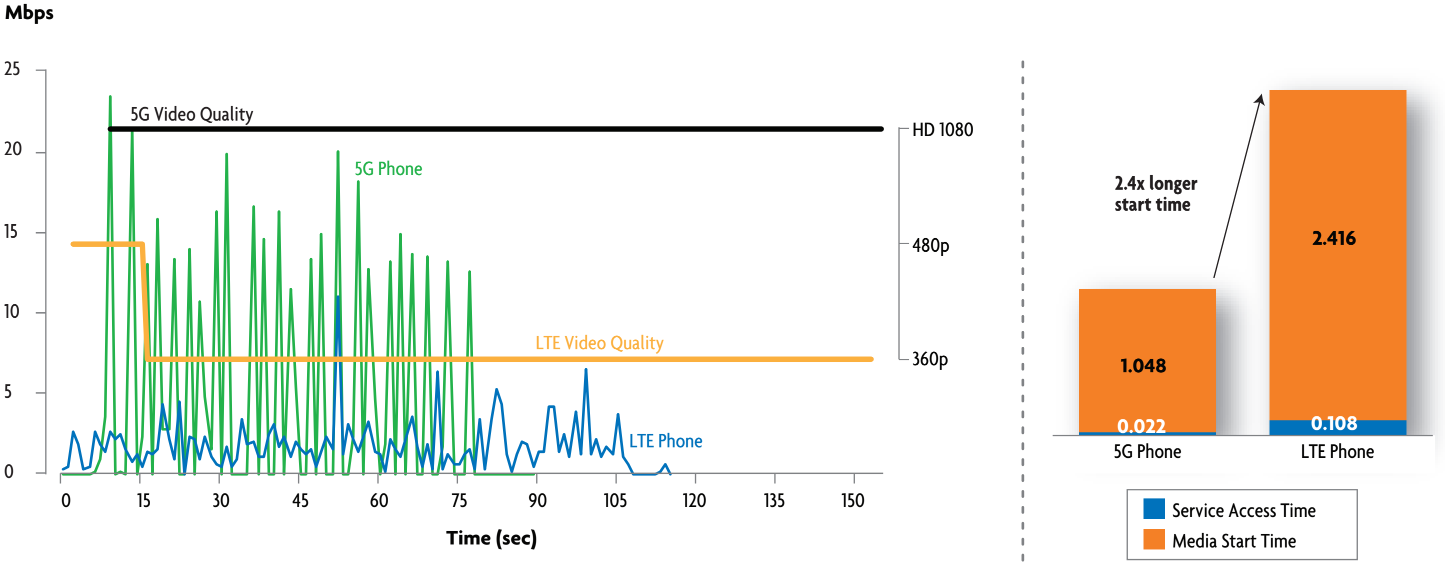
5G Capacity Gains Improves the User Experience, Especially in Capacity-Constrained Environments

In our testing in European 5G networks we focused our efforts on how 5G improves the user experience. For these tests, we used the smartphones to perform real-world usage scenarios, such as downloading content (videos, games, large files) and streaming videos. Although measuring network speeds with a popular measurement application seems to be all the rage in some circles, it doesn't represent a typical use case for most consumers. For purposes of this study, we also sought out locations and corresponding times of the day when the LTE network was likely loaded. Therefore, the low data speeds that we sometimes observed in the LTE networks are not indicative of a typical user experience, but they are experienced in certain situations.

While the 5G smartphone retained the 1080p video resolution, the LTE smartphone had to start with 480p before dropping to 360p due to network loading.

The first three figures in this section pertain to YouTube and they involve testing in London's Victoria Station during evening rush hour. In Figure 29, we show the physical layer throughput associated with streaming an HD 1080p video. For this test, we used two smartphones – one smartphone on 5G and one smartphone on LTE – and attempted to play the same YouTube video (a trailer of Aquaman). The video on the 5G smartphone played fine and it retained the 1080p resolution throughout the playback. In the case of the LTE smartphone, the video quality started at 480p ("Large") before quickly dropping to 360p ("Medium"). The application resorted to the lower video quality due to network loading. Because the video quality was lower on the LTE smartphone the associated physical layer throughput was also lower. Put another way, neither video stalled during the playback – the LTE smartphone took 2.4x more time to start playing the video – but the user experience was better with 5G due to the higher resolution video format.

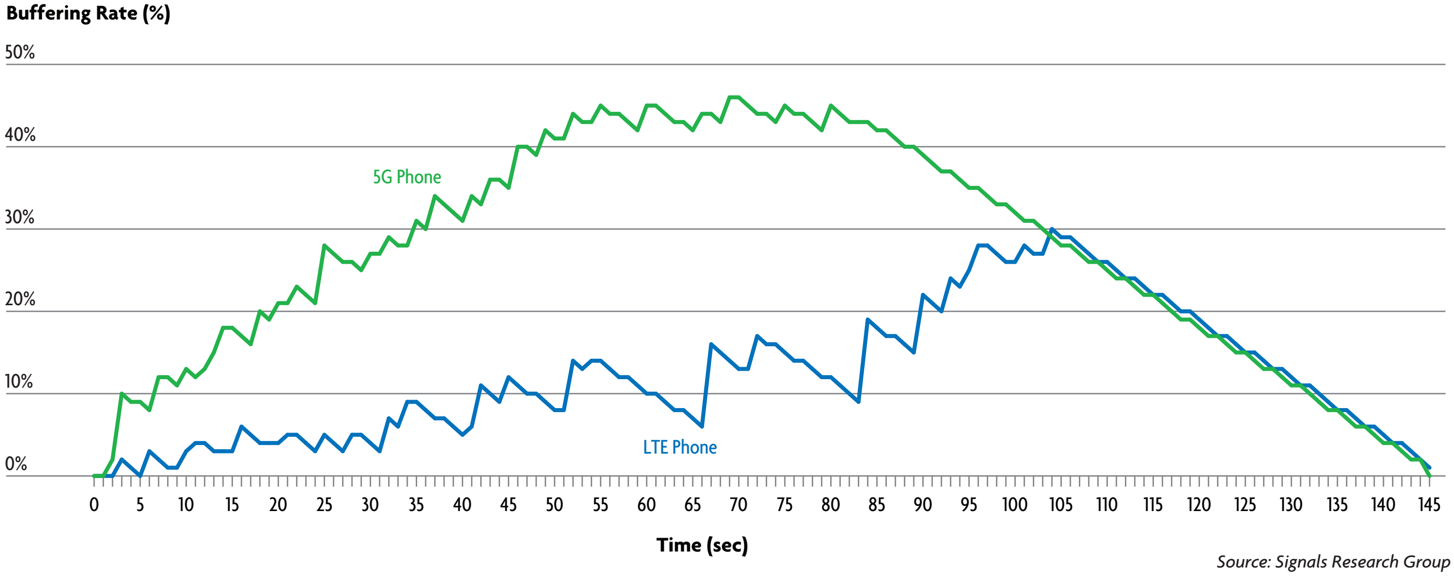
Figure 29. Physical Layer Throughput and Video Quality with YouTube Streaming – 5G vs. LTE



Source: Signals Research Group

In Figure 30 we've plotted the buffering rate for the two smartphones while playing the video. The buffering rate represents the difference between the amount of received video and the amount of played video. For example, a buffering rate of 50% could mean that 100% of the video has downloaded and that 50% of the video has played. A higher buffer rate is preferred since it means the video playback is less likely to stall. In this test, both smartphones had sufficient buffer throughout the test, but the LTE smartphone came close a few times to running out of content in the buffer, plus it took much longer for it to reach a stable level – note the slow ramp in the LTE Phone's buffering rate. Once the video has completely downloaded to the phone, the buffering rate will gradually decline until it reaches 0%, indicating the video playback has finished. The 5G smartphone finished downloading around 80 seconds and the LTE smartphone finished downloading the video around 105 seconds, despite playing a lower resolution video.

Figure 30. YouTube Buffering Rate – 5G vs. LTE

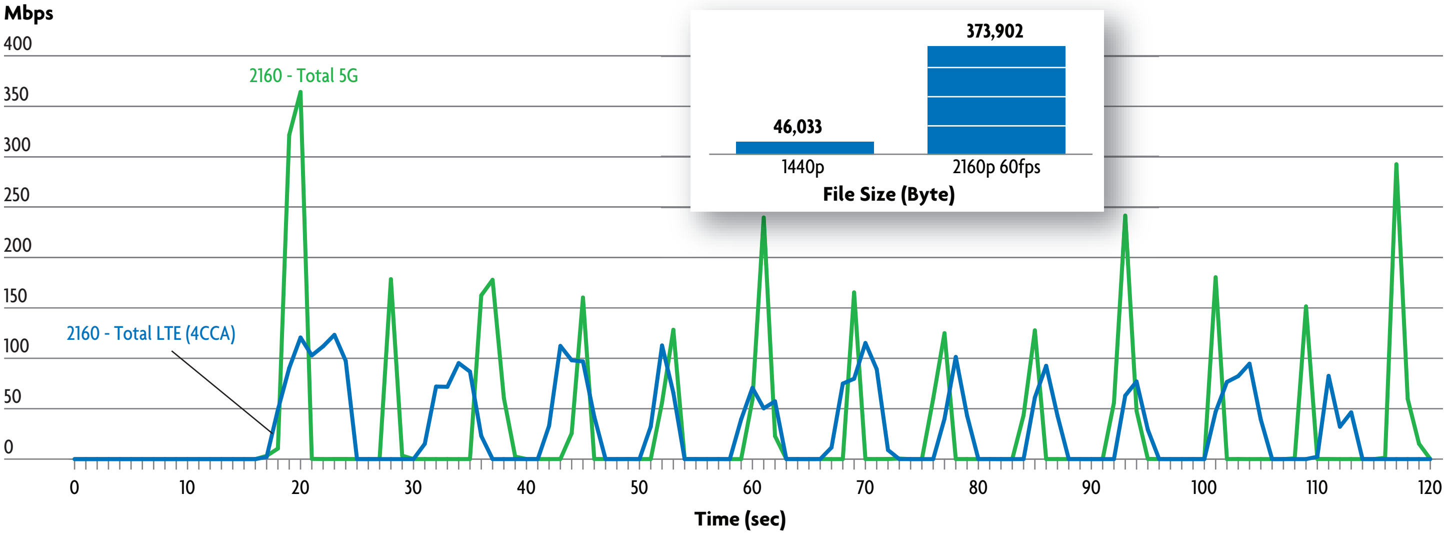


Source: Signals Research Group

A 4K video can generate 8.1x more data than a 1080p video.

Figure 31 illustrates the physical layer data speeds while streaming a 4K video. In this test, the LTE network was not capacity constrained, so it was able to play the video. However, the connection time to the LTE network was slightly longer than with the 5G phone since the peak speeds over LTE were lower than they were with the 5G phone. The inset in the figure shows the same video generates 8.1x more data than a 1080p video.

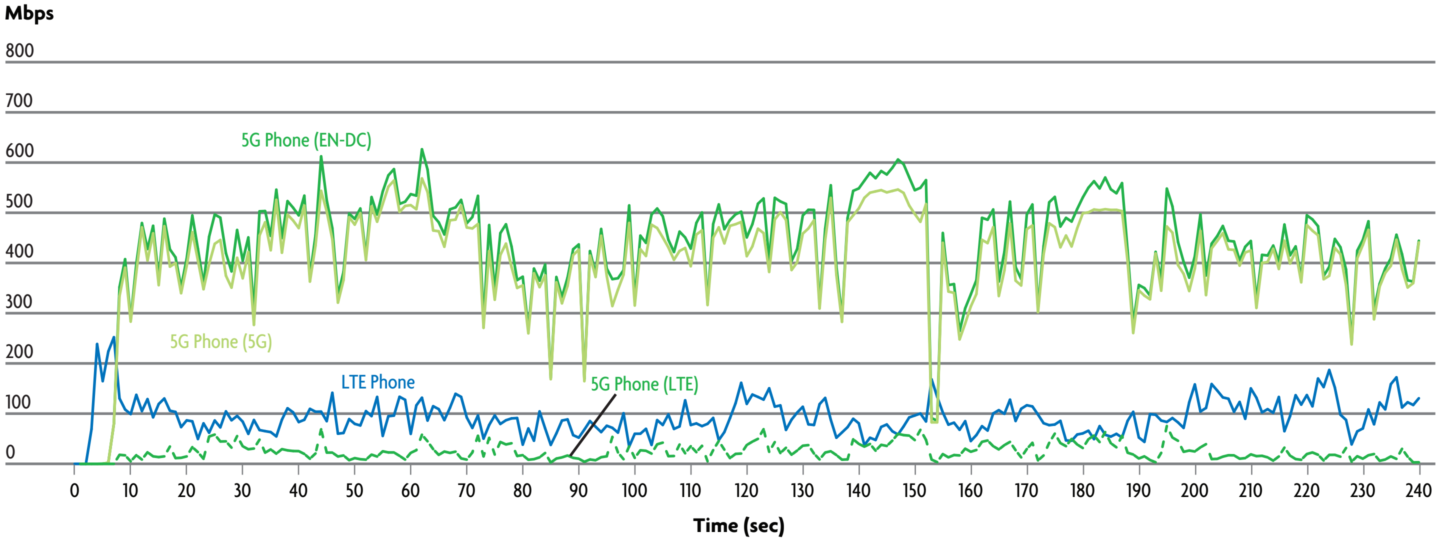
Figure 31. Physical Layer Throughput with 4K Video – 5G vs LTE



Source: Signals Research Group

Before concluding this section with a few figures that show results from other user experience tests, we are including Figure 32, which provides a time series plot of the physical layer data speeds for two smartphones downloading in parallel. The figure shows the LTE phone's data speed in one-second time increments as well as the average over the test (92.4 Mbps). The green color represents the 5G phone's data speed – the dashed line is the contribution from LTE, the light green line is the contribution from 5G, and the dark green color is the total (EN-DC) throughput. In this test, which involved using different applications to download multiple large files simultaneously, the 5G throughput was 446.3 Mbps, or 4.8x faster than the LTE smartphone.

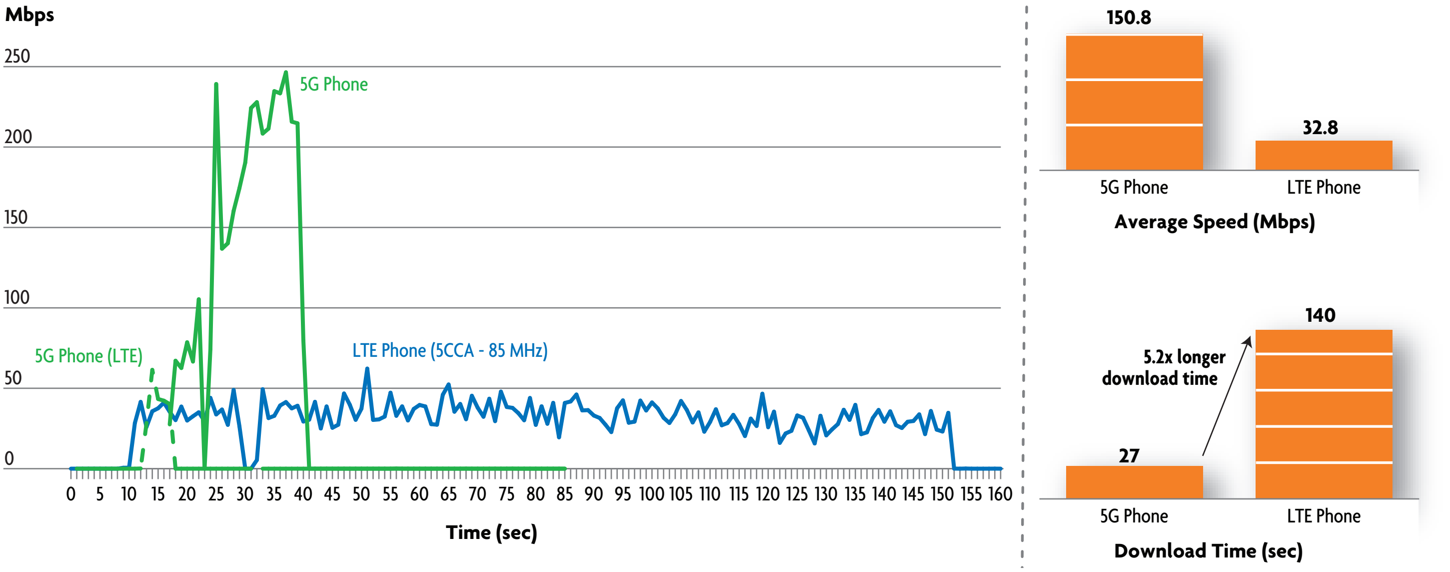
Figure 32. EN-DC Throughput and LTE Throughput – Bern Train Station



Source: Signals Research Group

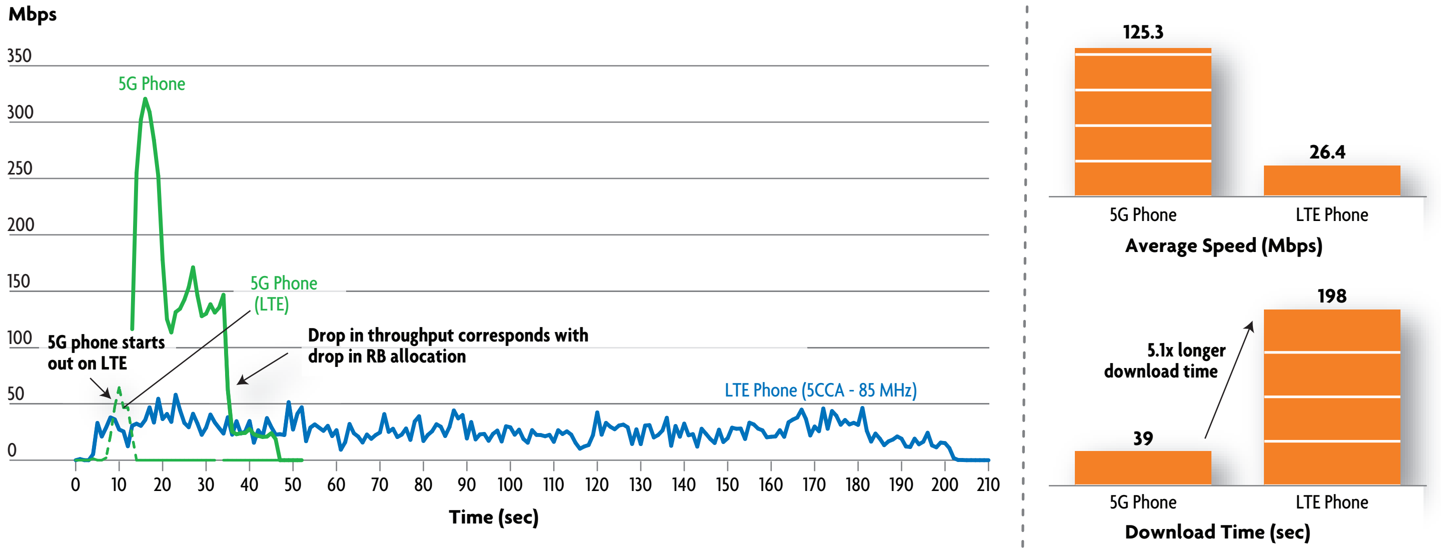
The last three figures in this section show the user experience when downloading content using popular websites and applications. Downloading a ~400 MB Angry Birds game from Google Play took 5.2x longer over LTE than it did over 5G, downloading the Johnny English movie from Netflix took 5.1x longer over LTE than it did over 5G, and finally downloading a home movie from Google Drive took 4.7x longer over LTE than it did over 5G.

Figure 33. Google Play (Angry Birds Game)



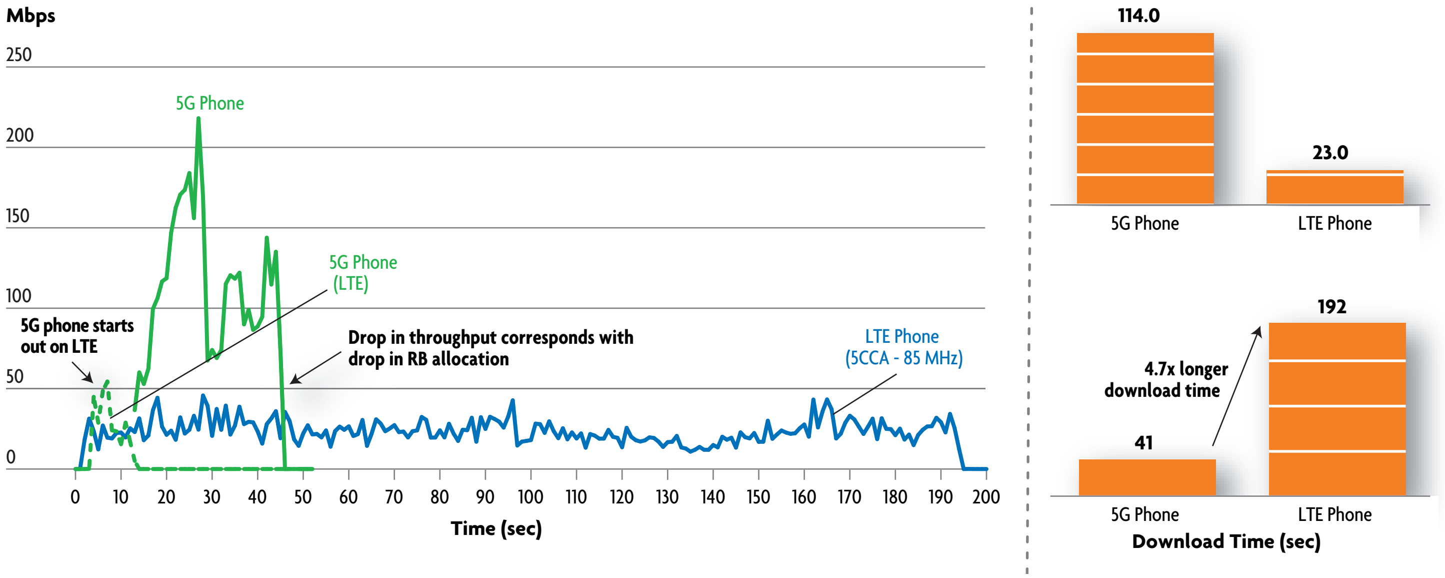
Source: Signals Research Group

Figure 34. Netflix (Johnny English Movie)



Source: Signals Research Group

Figure 35. Google Drive (Home Movie)



Source: Signals Research Group

By looking at the measured throughput in one-second increments versus simply measuring how long it takes to download the content, it is also possible to gain a little insight into what transpires during these data transfers. First, it is evident there is a lot of variation in the instantaneous data speeds during the file transfer. This situation is true for 5G and LTE, but it is more evident with 5G due to the relative magnitude of the data speeds. We don't believe the big drops in 5G data speeds were due to loading, but instead due to the behavior of the application/network since we see this type of behavior (a big peak followed by more moderate data speeds) in lots of our testing. Finally, it is evident that LTE played a minor role in contributing to the total data speeds of the 5G phone. With more contribution from LTE, the content would download faster, thereby improving the user experience.

The Energy Efficiency of 5G can Exceed that of LTE While Delivering a Full Day's Worth of Smartphone Usage

In late August we did testing in the Verizon Wireless 5G and LTE networks around Minneapolis, MN with two Galaxy S10 smartphones to examine the energy efficiencies of 5G and LTE, including the expected battery life of a smartphone with normal or abnormal usage. Over the course of the previous few months we read a few press articles lamenting about the battery life of a 5G smartphone and how it seemed to lose its energy supply much faster than an LTE smartphone. The commentary seemed anecdotal versus scientific, but since we hadn't investigated the topic, we didn't have a clear view either way.

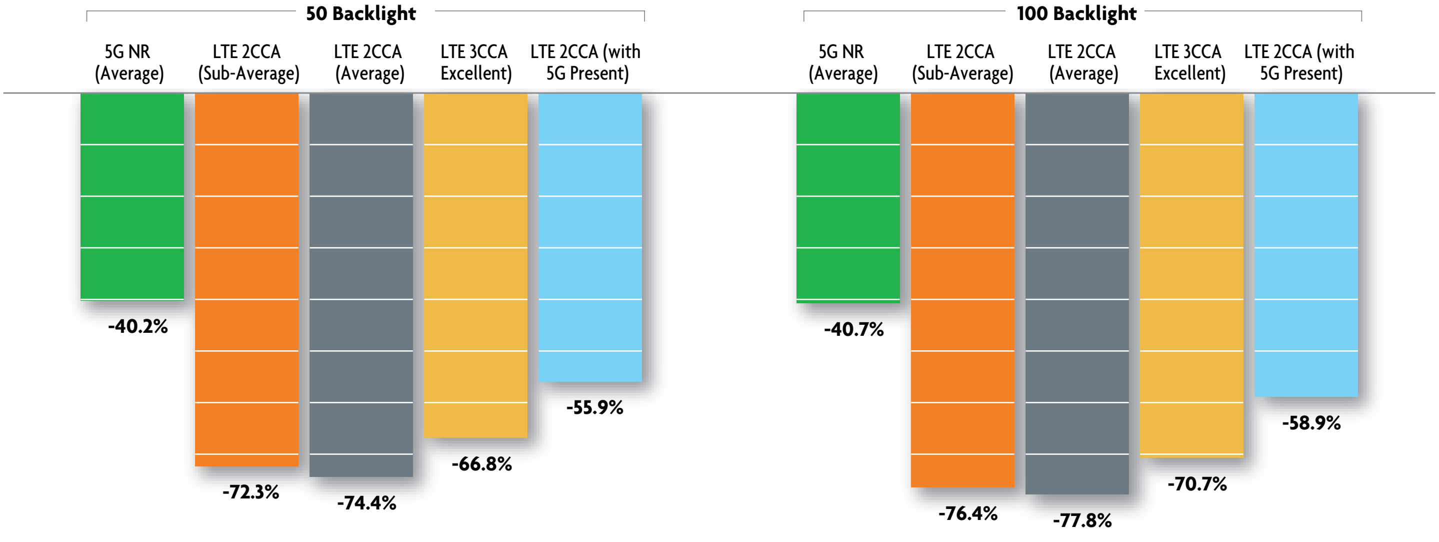
To summarize our test methodology, we measured the current drain of the battery in one-second time increments when the phone was in idle and airplane modes and with different backlight settings. We then did field testing in the LTE and 5G network by performing sustained downlink and uplink data transfers while concurrently measuring the application layer throughput (Umetrix) and the current drain. In our field testing, we included a range of radio conditions (strong and weak signals) as well as the use of LTE carrier aggregation – determined with the XCAL-Solo hardware and software. By testing in downtown Minneapolis, the suburbs, and in rural Minnesota, we were able to include 5G networks and LTE networks with 2CCA and 3CCA.

By comparing the application layer throughput and the current drain we were able to reach a few important conclusions.

- In good (not great) radio conditions, 5G is more energy efficient than LTE. Although the current drain is higher, it is offset by the much higher data speeds.
- When the data speeds are artificially throttled – for example, to replicate a video chat application – LTE is more energy efficient than 5G.
- A 5G-capable phone in idle mode or when connected to an LTE network, such as with a VoLTE call, has a higher current drain if it can detect the presence of the 5G network. We observe periodic spikes in the current which don't exist when the 5G smartphone is well outside the range of a 5G cell site.
- 5G downlink data transfers can be more than 20x energy efficient compared with uplink LTE data transfers. Granted, this observation is comparing apples and oranges, but the observation still has implications.

Figure 36 illustrates the energy efficiency from various test scenarios, compared with 5G and very good radio conditions. Although it isn't entirely clear in the figure, there is a strong correlation between measured data speeds and energy efficiency. This correlation isn't surprising since we found a similar trend when we analyzed the energy efficiency of LTE carrier aggregation several years ago – namely, LTE CA consumes more energy than LTE without carrier aggregation, but the higher data speeds of LTE CA more than makes up for the higher current drain. The "LTE 2CCA (with 5G Present)" data speeds from our most recent tests were the best LTE results and they stem from testing LTE in downtown Minneapolis where Verizon also has 5G coverage. We attribute the strong performance to the operator's use of small cells. Earlier in this paper we also highlighted the very favorable performance of the LTE network. The energy efficiency results are also influenced by the backlight display, so we are including two sets of results – backlight at 50% and backlight at 100%.

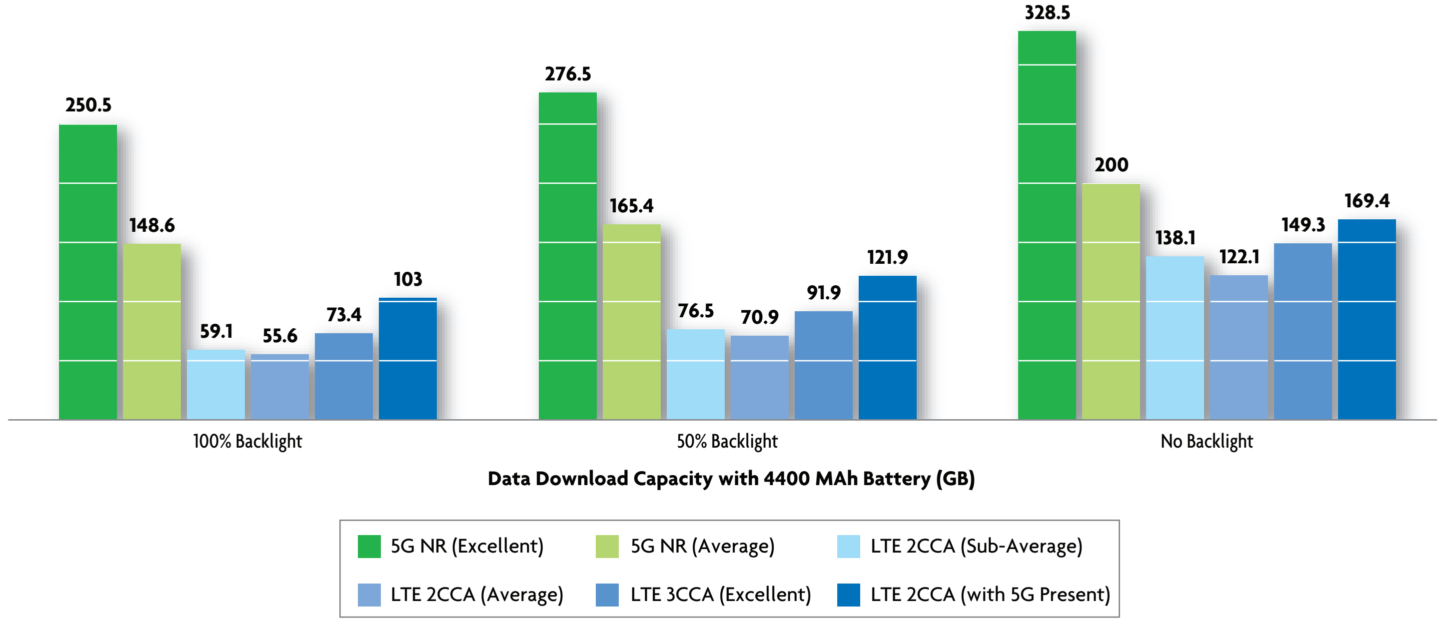
Figure 36. Energy Efficiency Relative to 5G with Maximum Throughput



Source: SA 09/09/19, "Un-plugged!" – Figure 6

In Figure 37 we combine the current consumption and observed data speeds to show how much data the Galaxy S10 smartphone could download with a 4400 mAh battery. The Galaxy S10 smartphone has a 4500 mAh battery with a minimal rating of 4400 mAh so we used the more conservative value. The results show that a 5G enabled smartphone can download considerably more data than an LTE-only smartphone. The amount of data drops with a brighter backlight display since the display is also consuming energy.

Figure 37. 5G and LTE Data Download Capacity with a 4400 mAh Battery



Source: SA 09/09/19, "Un-plugged!" – Figure 7

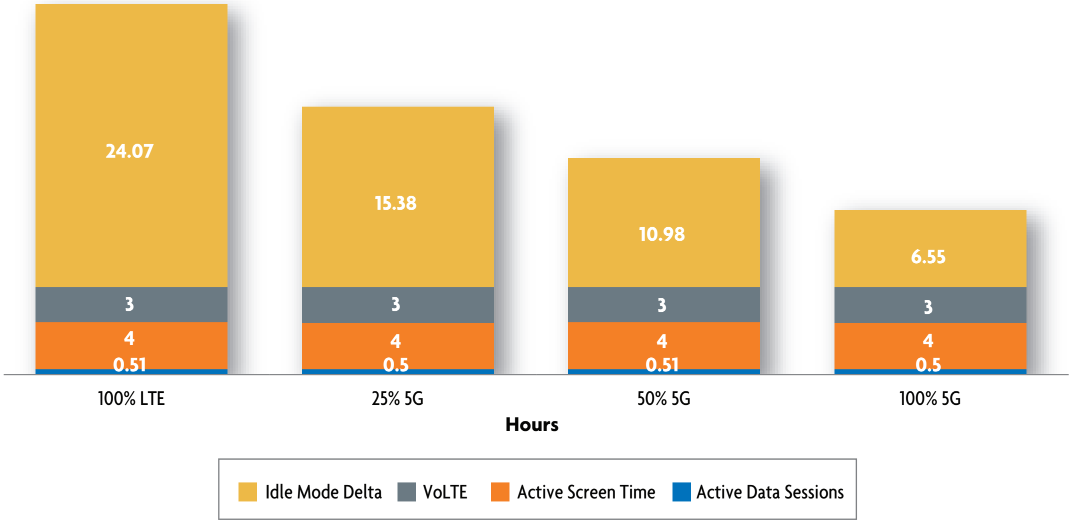
The information in Figure 37 is interesting but no one uses their phone in this manner. Instead, a typical consumer snacks on mobile data throughout the day, uses the phone to make voice calls, and activates the phone's display to perform other functions (play a game offline, take a picture, view a photo gallery, etc.). With this in mind, we created several viable solutions involving a mix of LTE and 5G usage to determine the estimated battery life. Figure 38 shows the results from one set of assumptions.

For starters, we assumed the consumer downloaded 1.5 GB of data in a single day – 90% in the downlink and 10% in the uplink. Since this usage equates to ~45 GB per month, or well above most rate plans, it is clearly a lot of mobile data. Taking it one step further, we assumed that 80% of the downlink data, or 1.35 GB, was downloaded at a data speed of only 5 Mbps, 10% of the data was downloaded at 30 Mbps and 10% of the data was downloaded at the maximum speed (exact values taken from our field measurements). Our selection of these values is somewhat arbitrary, but it reflects the realization that a consumer's data activities frequently do not generate maximum downlink transfers. Video chat applications, for example, only generate ~5 Mbps of downlink and uplink data speeds while 4K video requires a continuous data speed of ~30 Mbps. This assumption also severely penalizes 5G since its higher energy efficiency is predicated on leveraging the high data speeds that the technology delivers. We also assumed a 50% backlight display, 3 hours of VoLTE calls, and 4 hours of the display turned on for non-communications activities. The text below the four bars reflects the distribution of usage between LTE and 5G. For example, "25% 5G" means that 25% of the data went over 5G and 25% of the data went over LTE (VoLTE is entirely LTE in all cases).

Once we calculated the amount of energy required for these activities, we assigned the remaining portion of the energy to idle time. Since the current drain of a phone is idle mode is lower in an LTE network than in a network where 5G is present, due to the periodic spikes in current consumption that we mentioned earlier in this section, the estimated battery life is longest for "100% LTE". However, in all scenarios, the total estimated battery life was at least 14 hours, or sufficiently long enough for most workdays.

Figure 38. Distribution of Energy Budget with Varying Allocations Between 5G and LTE – in hours

Key Assumptions
1.5 GB Data Transfer; 50% Display Brightness; 10%/10%/80% split; 90% DL/10% UL; no gross up of transfer time; 3 hours of VoLTE and 4 hours of active display with a 1.2x multiplication factor to reflect non-communications usage; Idle time spent on the same network, mix of networks, based on the corresponding usage



Source: SA 09/09/19, "Un-plugged!" – Figure 30

A 30-minute gaming session of Solitaire can be the equivalent of downloading more than 30 GB of data with a good (not great) 5G connection.

Although this scenario doesn't conclusively prove that a 5G smartphone can go an entire workday on a single charge, it does provide strong evidence that it should last a full day. Furthermore, to the extent a battery doesn't last a full day, it is most likely due to factors other than 5G data connectivity. According to our calculations and results from our field measurements, a 30-minute gaming session of Solitaire can be the equivalent of downloading more than 30 GB of data with a good (not great) 5G connection.

It is also important to note that we are currently testing with first-generation 5G solutions that include separate modems for LTE and 5G. With next-generation solutions, this circuitry will be integrated, plus we expect tighter interworking between the RF front end and the baseband modem, not to mention increased efficiencies in the performance of the RF front end. These factors should help reduce the energy consumption that exists today in 5G smartphones.

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.

The data transfers – downlink and uplink – typically last for at least sixty seconds and frequently up to three minutes. The longer data transfers are essential when evaluating network features, such as handovers between cells or handovers between beam indices within a cell. A simple data speed test with a popular consumer application only lasts 10-20 seconds, which isn't useful when evaluating critical network features. Following each data transfer, the test scenario recycles and starts again. During this brief period there isn't any data connectivity, hence in some of the plots there are brief periods when there are not any observed data speeds.

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. Accuver Americas has also integrated its solutions with the PCTEL and 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 capture.

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 have also used the Umetrix video platform when doing video quality analysis for multiple studies that we have done over the last few years. The Umetrix data platform allows us to select the protocol (UDP or TCP) and determine the number of concurrent threads. Typically, we try to push as much data as possible to maximize the observed data speeds, but in the case of the energy efficiency tests, we artificially set the data speeds to lower values. The Umetrix tools are also integrated with the WirelessMETRIX Link Master Logger (LML) logging tool and the Link Master Analyzer (LMA) post-processing software. We used this integrated solution – Umetrix to generate data transfers and log application layer throughput and LML/LMA to capture and analyze lower layer metrics – when we tested in US Bank Stadium.

We used the PCTEL HBflex scanner when we recently did 5G testing in Chicago and Minneapolis. The scanner, which comes in a self-contained backpack with a battery pack, supports either millimeter wave or sub 7.125 GHz frequencies so we were able to use it when testing two different networks. A simple switching of antennas was all that it took to go from 28 GHz to 2.5 GHz. Equally useful, the HBflex scanner integrates with XCAL-Solo and XCAP, making it relatively straight-forward to collect and analyze log files.

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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