WHAT GOES AROUND, COMES AROUND

A THIRD-PARTY BENCHMARK STUDY OF mmWAVE DEVICE + CHIPSET PERFORMANCE

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Prepared by
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SIGNALS Research Group
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Study Conducted for MediaTek

As the sole authors of this study, we stand fully behind the results and analysis that we provide 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* research newsletter (www.signalsresearch.com)

1.0 Key Highlights

Signals Research Group (SRG) conducted a performance benchmark study of 5G mmWave smartphones and chipsets, representing chipsets from the three traditional 5G chipset suppliers. Table 1 identifies the smartphones we tested as well as provides basic information about each of the phones.

Table 1. Smartphones Under Test

Smartphone Model	Manufacturer	Intro Date	Modem Supplier	5G Chipset/Processor	List Price (at launch)
Galaxy S22 5G (SM-S901U1)	Samsung	Feb-22	Qualcomm	Qualcomm Snapdragon 8 Gen 1 / X65	$800
Pixel 7	Google	Oct-22	Samsung	Tensor G2 chipset / Exynos 5300g	$700
Motorola edge 5G UW (2021)	Motorola	Oct-21	Qualcomm	Qualcomm Snapdragon 778G / X53	$550
Motorola edge (2022)	Motorola	Aug-22	MediaTek	MediaTek Dimensity 1050	$660
MediaTek MTP	MediaTek	N.M.	MediaTek	MediaTek Dimensity 1050	N.M.

Source: Signals Research Group and various websites

We note there are noticeable differences in price points – partly driven by additional features and functionality – as well as differences in release dates. This selection of phones, however, covers the gamut of what we wanted to include in the study while allowing for some interesting comparisons. We didn't include higher priced models, such as the Galaxy S22 Ultra and the Google Pixel 7 Pro, but based on our prior experience, we believe their RF performance would be comparable to the lower priced models (e.g., Pixel 7 and S22) we did include in this study.

We also included a MediaTek MTP (Mobile Test Platform) as an additional reference point, while acknowledging its design and larger size could be more conducive to better mmWave performance with the tradeoff being a higher bill-of-material. We only benchmarked the MTP against the Motorola edge 2022 smartphone, which also had a MediaTek modem inside.

The primary focus of this benchmark study was on the beam tracking capabilities of each smartphone/5G modem. As we've written in earlier reports, even dating back to times prior to our first experience with 5G mmWave, the challenge isn't so much having a usable mmWave beam available, but the smartphone's ability to select and lock onto the best available beam using the two or more RF mmWave modules located within the smartphone.

The primary focus of this benchmark study was on the beam tracking capabilities of each smartphone/5G modem.

Beam selection is relatively straightforward in a stationary/static environment, but it becomes more challenging when the smartphone is mobile or when the 5G mmWave signals from the serving 5G base station (gNB) to the smartphone are changing their directional path, for example due to blockage/partial blockage or other fading caused by changes in the environment. A passing bus is a good example. To identify potential performance differences between the chipsets/devices that we tested, we leveraged a rotating platter to expose the two smartphones under test to the same constantly changing RF environment and the subsequent need for continuous beam selection. In each test we used the Motorola edge 2022 smartphone (MediaTek 5G modem) as the benchmark phone along with one of the other smartphones listed in the table.

Key highlights from our benchmark testing include the following:

Depending on the RF environment, it wasn't uncommon for the MediaTek-enabled devices to obtain double-digit higher throughput along with a double-digit lower variation in their instantaneous throughput.

- The MediaTek 5G modem frequently exhibited an obvious advantage over its peers when subjected to our controlled test environment. With static conditions (i.e., the platter wasn't rotating), the performance differences were less significant, although they tended to favor the Motorola edge 2022 smartphone (MediaTek modem). When the platter started rotating, either with line-of-site (LOS) or non-LOS conditions, it was more evident the throughput advantage favored the MediaTek-based devices. Closer to the cell site, the throughput advantage was less meaningful (~5% to ~15%) but at greater distances or NLOS conditions the throughput advantage was more pronounced (~10% to 40+%), depending on the smartphone used in the test.

- The rotating platter impacted the throughput of all smartphones/chipsets, but the impact was generally much less with the MediaTek-based smartphones. Again, the RF conditions played an underlying role, but it wasn't uncommon to observe the MediaTek-based devices frequently having at least 20% lower variations in their throughput relative to the non-MediaTek smartphones with more challenging test conditions. For reasons discussed later in this report, it wasn't logistically possible to test with more challenging RF conditions beyond what we did in this study. Had we been able to do so, we believe the differences in performance would be even more significant than shown in this report.

- Based on our results, we can attribute the higher throughput and lower variation of the throughput observed by the MediaTek-enabled smartphones to the beam tracking capabilities of the MediaTek 5G modem. With static conditions (no platter rotation), we show the Samsung Galaxy S22 (QC) and Motorola edge 2022 smartphone (MediaTek) both reported solid/unchanging MCS values, CQI reports and SINR/RSRP measurements. Additionally, we show the two phones/chipsets didn't alter their internal means of receiving and processing the best mmWave signal. When the platter started rotating, both phones/chipsets exhibited variations in these parameters, but the variations were much lower with the Motorola edge 2022 smartphone (as well as with the MediaTek MTP). We also show how both smartphones/chipsets started adjusting how they received and processed the best mmWave signal while rotating. These adjustments play a critical role in optimizing RF performance, but the data indicates the beam selection process used by MediaTek delivered both higher throughput and lower variations in the throughput in most instances.

A special thanks to Accuver Americas and Spirent Communications for the use of their respected test equipment. Both companies have been invaluable partners to these types of studies for well more than a decade. SRG takes full responsibility for the data collection and analysis of the results. We describe their products and how we used them in the test methodology chapter.

The following sections of this paper support the comments made in this executive summary.

Table of Contents

Index of Figures

2.0 Background

SRG is a US-based research consultancy that has been in existence since 2004. We publish a subscription-based research product called *Signals Ahead,* which has corporate subscribers that span the globe and involve all facets of the wireless ecosystem. Our corporate readership includes many of the largest mobile operators in the world, the leading infrastructure suppliers, subsystem suppliers, handset manufacturers, content providers, component suppliers, and financial institutions.

SRG is a US-based research consultancy that has been in existence since 2004.

One key focus area of our research where we are widely recognized is our independent and third-party benchmark studies. These studies have taken us all over the world to test emerging cellular technologies and features immediately after they reach commercial status. As an example, since the launch of the world's first 5G network in 2018, we've published 30 benchmark studies in Signals Ahead as of January 2023 pertaining to the next generation technology. These studies have included a wide range of frequencies, device, and chipset performance, not to mention new features within 5G and how 5G impacts the user experience with frequently used mobile applications.

One key focus area of our research where we are widely recognized is our independent and third-party benchmark studies.

This paper focuses on chipset + device testing in downtown Minneapolis, where we have done numerous 5G mmWave-related studies. We even tested at many of the same 5G mmWave sites that we have used in the past. In Minneapolis, the network was limited to 400 MHz (4x100 MHz) of spectrum. We recognize the two MediaTek-based devices that we tested only supported 400 MHz of spectrum and that many 5G mmWave smartphones, including the Galaxy S22, support the full 800 MHz of spectrum, which would result in higher throughput. However, the focus of this study was on the beam tracking capabilities of the smartphones/chipsets which is a key performance feature, regardless of the supported channel bandwidth.

This paper focuses on chipset + device testing in downtown Minneapolis, where we have done numerous 5G mmWave-related studies in the past.

We also leveraged the same methodology that we have used in the past to analyze collected data, including from some smartphones where we only had access to application layer performance. Given the focus of the study, and our belief that we needed a more rigorous and highly-repeatable process to collect the data, we did alter how we conducted our testing for this study. We explain our test methodology later in this paper.

We include results from testing the various smartphones + chipsets at three different locations in downtown Minneapolis on the Verizon 5G mmWave network. At one of the locations, we placed the platter holding the smartphones in two positions, one with a direct line-of-site (LOS) view of the 5G mmWave radio and the second with a partially/fully blocked view of the 5G mmWave radio. We had hoped to include a complete set of results from one of these locations, but we later discovered the Motorola edge 2022 battery level was below 10%, resulting in the phone entering a power saving mode during which time its performance could have been impacted in unknown ways. Since we didn't discover the implications of the low battery until we started analyzing the data, we weren't able to include comparative results with two of the smartphones. Luckily, we switched to a second Motorola edge 2022 smartphone that we had in our possession, so we are able to include a partial set of results from this location.

We also wanted to test with more challenging 5G mmWave radio conditions, but we quickly observed the operator had established a very conservative handover threshold between 5G mmWave and Band n77. Put simply, with the more challenging conditions we sought, the smartphones would drop to Band n77 even though the 5G mmWave radio conditions were sufficient to deliver meaningful data speeds. We've observed this phenomenon in previous tests that we've done in this market and noted as much in a recent Signals Ahead report. We believe, but were unable to prove, that if we tested in more challenging 5G mmWave RF conditions that the performance differences we observed between the MediaTek-enabled smartphones and the other smartphones used in this study would have been greater than the differences documented in this study.

We were unable to test with more challenging 5G mmWave radio conditions due to very conservative handover parameters between the 5G mmWave and Band n77 network.

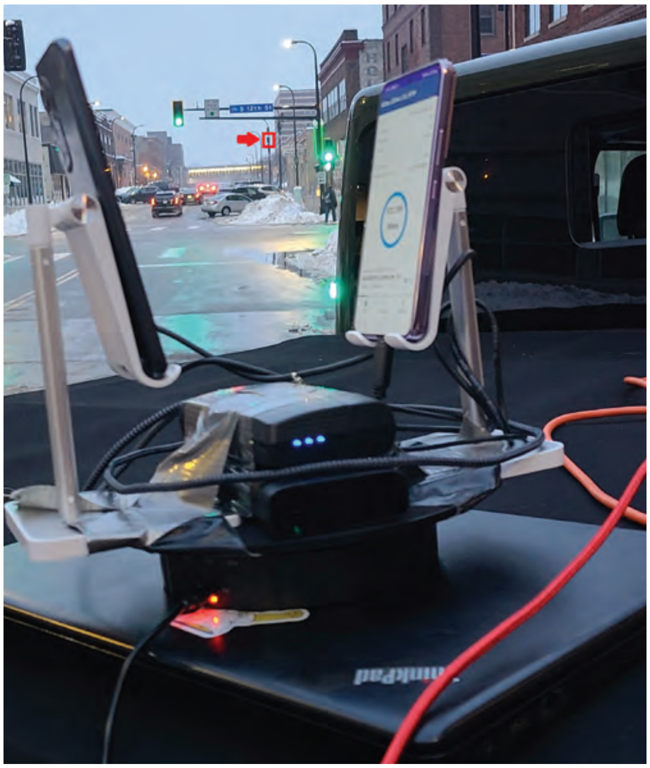
For all tests, we collected application layer throughput using the Umetrix data platform. With two smartphones we were able to expose the chipset diagnostic port, so we also provide our analysis of physical layer parameters with the Samsung Galaxy S22 and Motorola edge 2022 smartphones. Having physical layer parameters allowed us to conduct a richer analysis of the data while also allowing us to confirm the application layer throughput resulted in credible results that were consistent with the physical layer information.

We used a combination of application layer and physical layer results when analyzing the performance of the smartphones/chipsets.

3.0 Location 1 Test Results

Figure 1 shows a picture of the serving 5G mmWave radio, taken from this test location. Based on our measurements using Google Earth, the site was 150 meters away from where we did these tests.

Figure 1. Test Location



Source: Signals Research Group

3.1 Motorola edge 2022 and Samsung Galaxy S22

This section contains the results for the Motorola edge 2022 and Samsung Galaxy S22 smartphones. We include both application layer and physical layer results for these two smartphones.

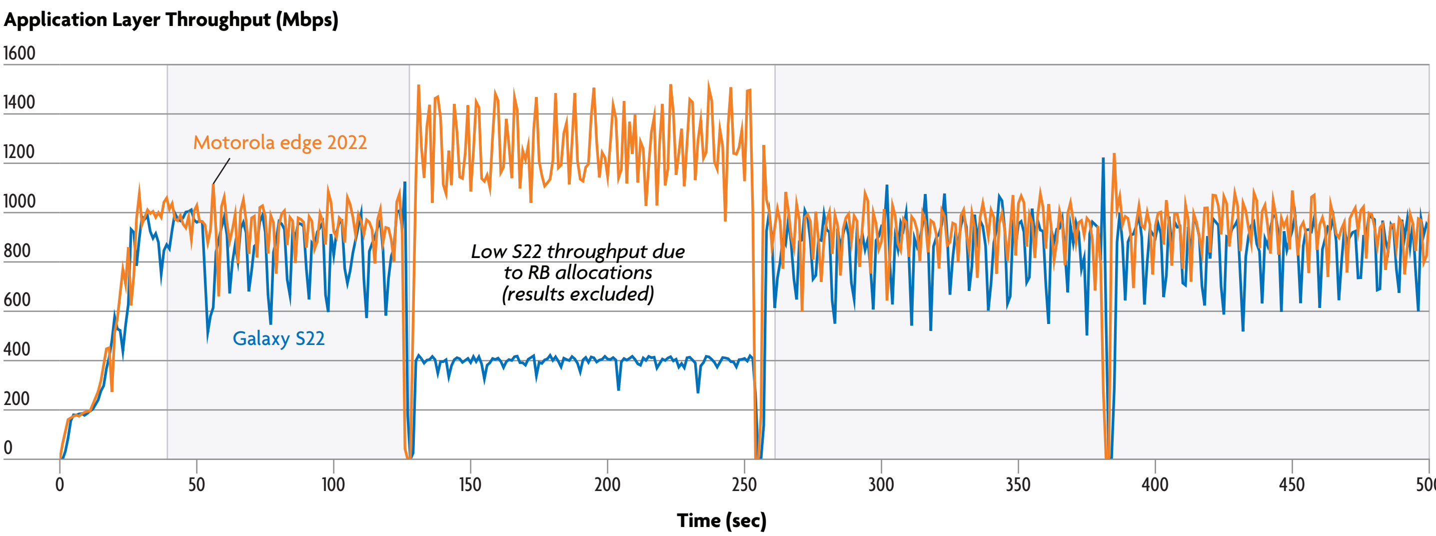
Figure 2 provides the application layer throughput for the two smartphones from the test at this location. In the figure, we shaded those areas of the test that we included when doing the analysis. In all tests, there was a short period at the beginning when the smartphones were receiving data, but the platter was not rotating. Additionally, in many tests there was a slow TCP ramp in the throughput for one or both smartphones, and we excluded this period as well. This phenomenon could be the result TCP window sizing issues within the network or at the mobile device, but in any event, it is not related to RF performance, which is the focus of this study. In this test, the network scheduled far more network resources to the edge 2022 smartphone than the S22 smartphone (illustrated in a subsequent figure) during one data transfer session, so we excluded this portion of the test as well. We point out the brief downward spikes which occurred roughly every 120 seconds in this figure and in subsequent figures were due to the periodicity of the Umetrix data transfer sessions, which ran repeatedly until we ended the test.

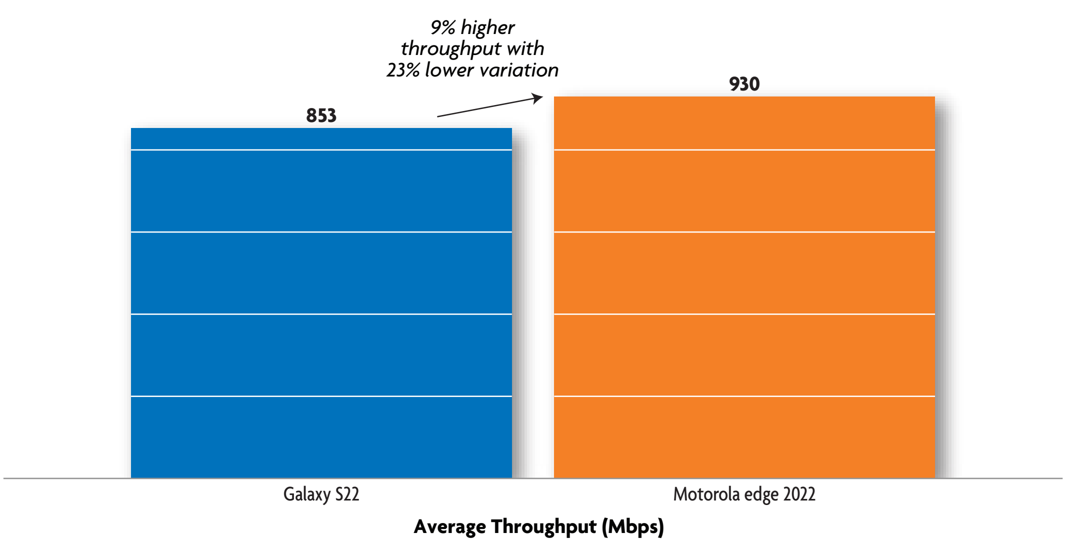
The brief downward spikes in the throughput were due to the periodicity of the Umetrix data transfer sessions, which ran repeatedly until we ended the tests.

Based on our analysis of the data, the edge 2022 smartphone achieved 9% higher application layer throughput than the S22 smartphone. More importantly, we can attribute the better performance of the edge 2022 smartphone to the higher variability of the S22 smartphone's throughput. The differences in the variability of the throughput for the two smartphones is evident in the time series plot. As we will prove later in this section, we can directly attribute the variability in the throughput to the rotation of the smartphones and their ability to remain locked on the "good signal." As explained in the test methodology section, we define the variability as the standard deviation of the throughput divided by the average throughput.

The edge 2022 smartphone achieved 9% higher application layer throughput with 23% lower variability than the S22 smartphone.

Figure 2. Motorola edge 2022 and Samsung Galaxy S22 Application Layer Throughput



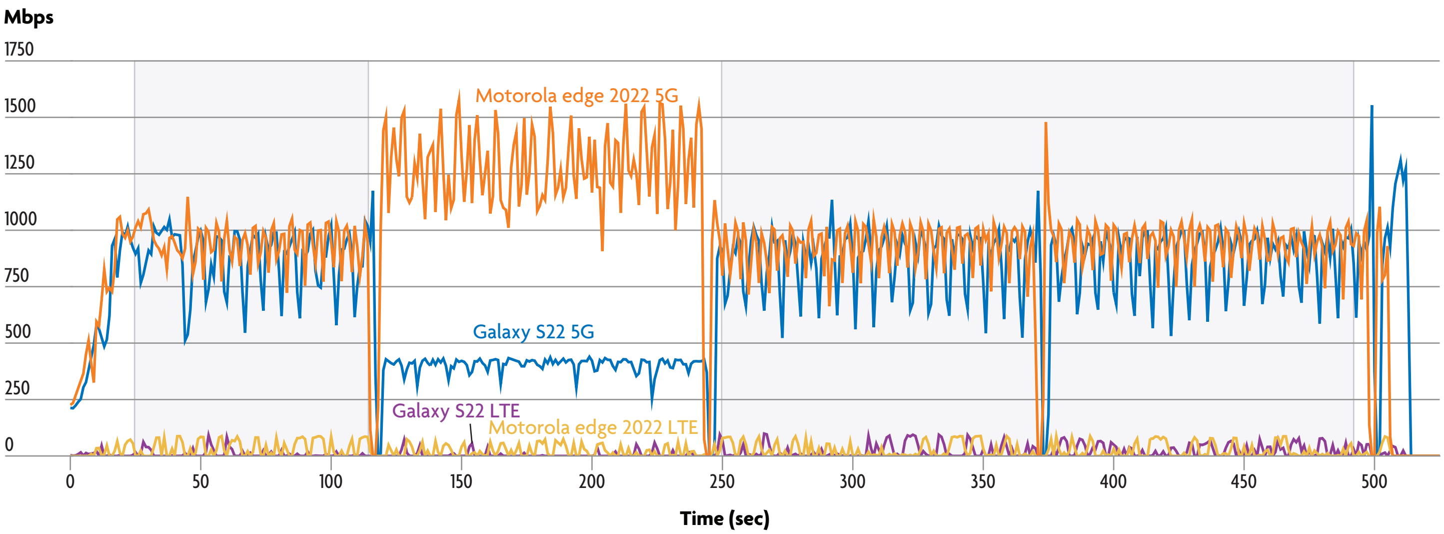


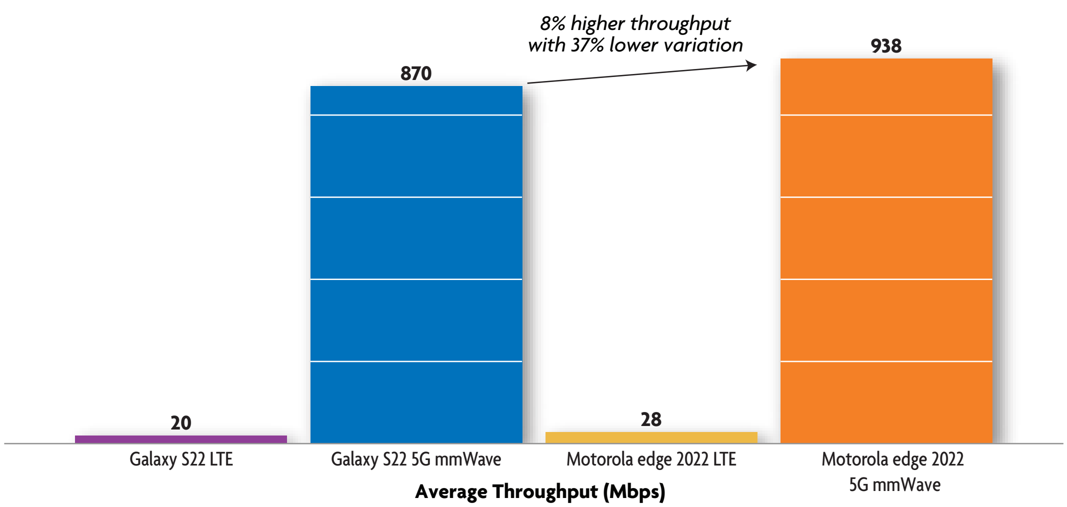
Source: Signals Research Group

Figure 3 shows the physical layer throughput for the two smartphones during this test. Since this information came directly from the chipsets in the two smartphones, we were able to separately identify the contributions from LTE and from 5G mmWave, including each of the four component carriers (not shown in this figure). Not surprisingly, the time series figure looks very similar to the comparable figure in Figure 2. More importantly, the information confirms that the contribution from LTE was insignificant for both smartphones, or only two to three percent of the total physical layer throughput. Based on this information, as well as other test results using these two smartphones, we can conclude that the LTE layer throughput for all smartphones in this study was insignificant and that it had no discernable impact on the results. This observation is consistent with other 5G mmWave testing that we have done in Verizon markets over the last two years.

The LTE layer throughput for all smartphones in this study was insignificant and it had no discernable impact on the results.

Figure 3. Motorola edge 2022 and Samsung Galaxy S22 Physical Layer Throughput

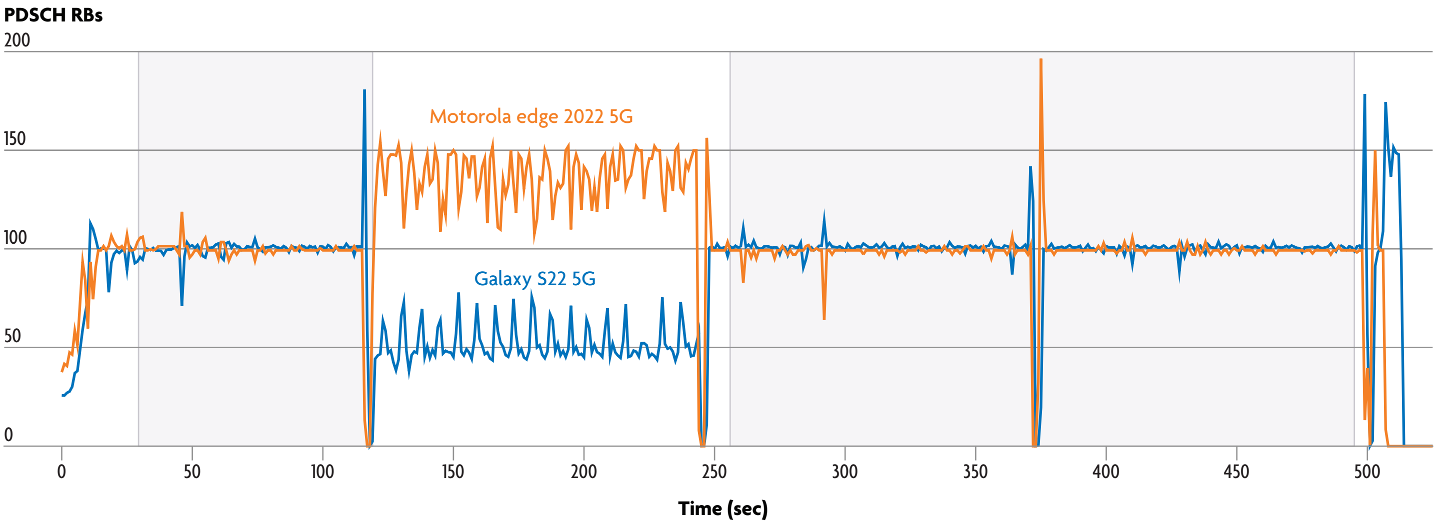


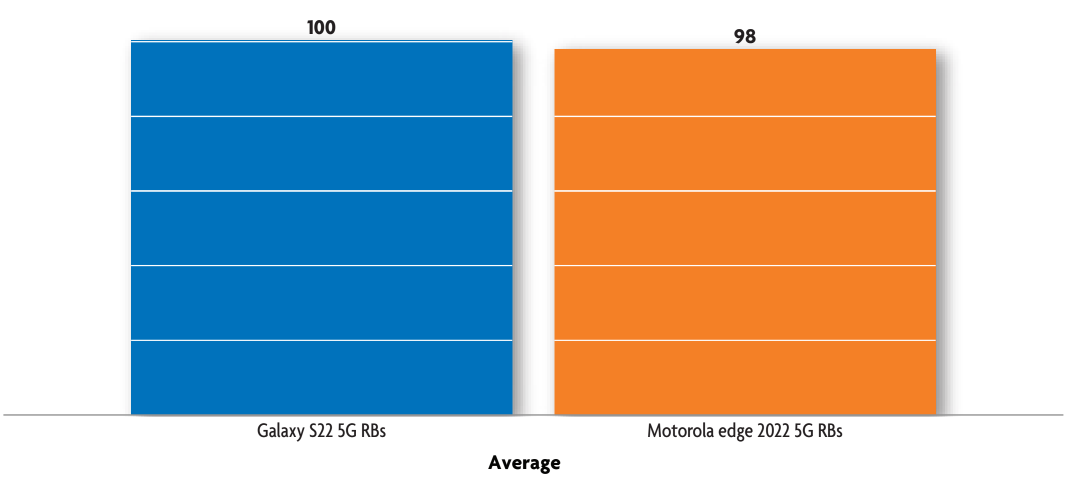


Source: Signals Research Group

Figure 4 shows how the scheduler allocated network resources (PDSCH Resource Blocks) to the two smartphones. Excluding the region between approximately 125 and 250 seconds, the network gave each smartphone equal access to the network with a nearly equivalent number of allocated resource blocks. We can't explain why the Galaxy S22 was allocated substantially fewer RBs during the second data session, and we haven't encountered something so dramatic in past benchmark studies. Nonetheless, we are pretty certain it wasn't phone-related, so we excluded this region from our analysis.

Figure 4. Motorola edge 2022 and Samsung Galaxy S22 PDSCH Resource Block Allocations

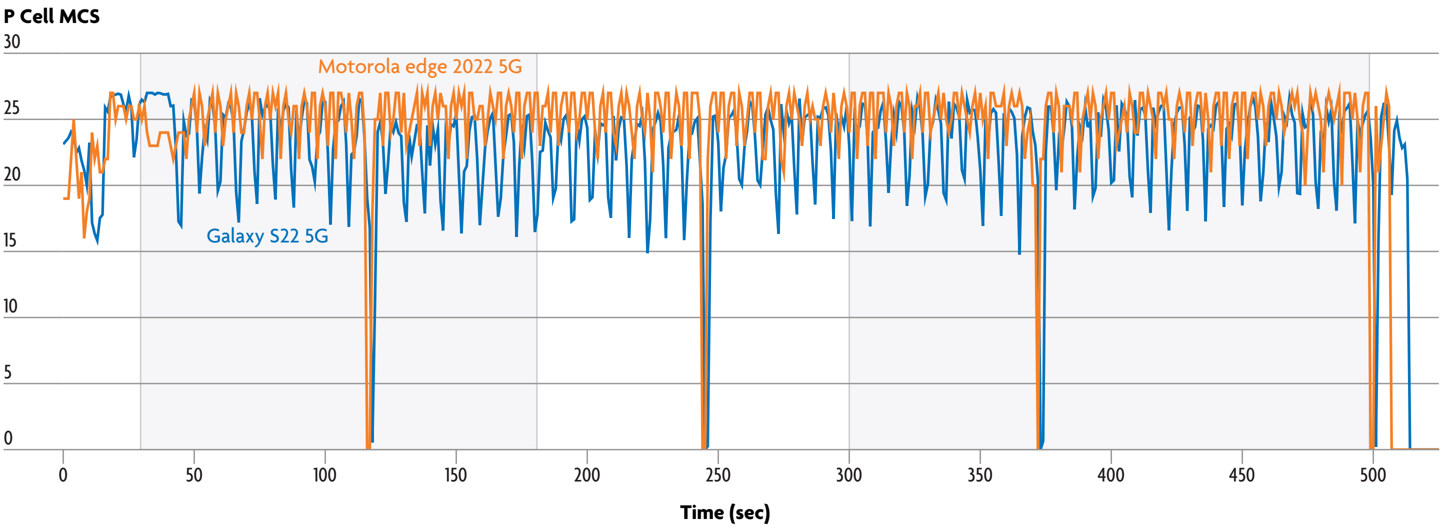


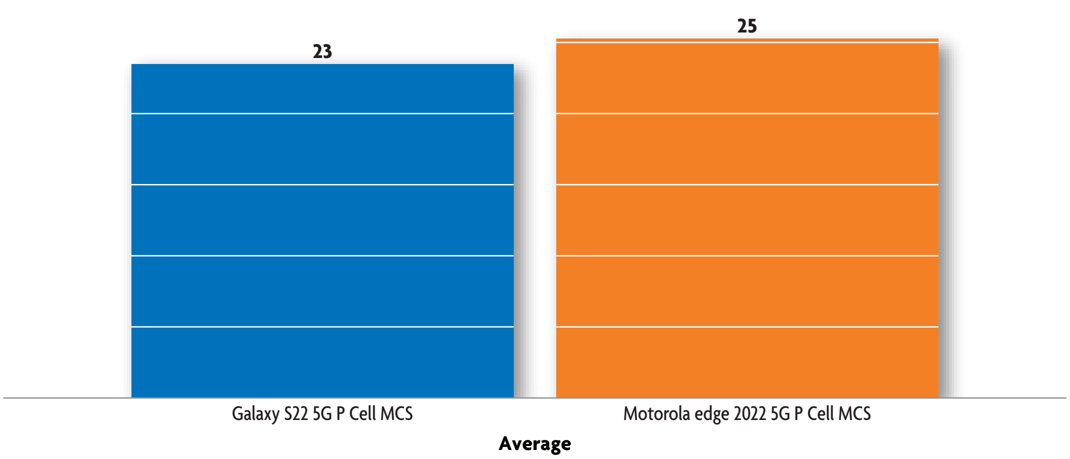


Source: Signals Research Group

In Figure 5 we illustrate the MCS (Modulation and Coding Scheme) values used by the two smartphones during the test. A comparison of the MCS values used by the two smartphones provides another means of evaluating their relative performance, and to some extent it is a better means of doing the analysis than using throughput. The latter is widely understood, but it can be influenced by how the network scheduler allocates resources, as shown earlier in Figure 3. For example, we can observe in Figure 5 that the MCS values used by the two smartphones were not influenced by the unexplained drop in RBs experienced by the Galaxy S22 during the second data transfer. We attribute the variability in the MCS values during the first twenty seconds of the test to activities associated with placing the two smartphones on the rotating platter. Once the platter started rotating, the average Motorola edge 2022 MCS values were higher than they were for the Galaxy S22 (MCS 25 versus MCS 23), almost entirely due to the higher variability in the MCS experienced by the S22 smartphone.

Figure 5. Motorola edge 2022 and Samsung Galaxy S22 Primary Cell MCS Allocations

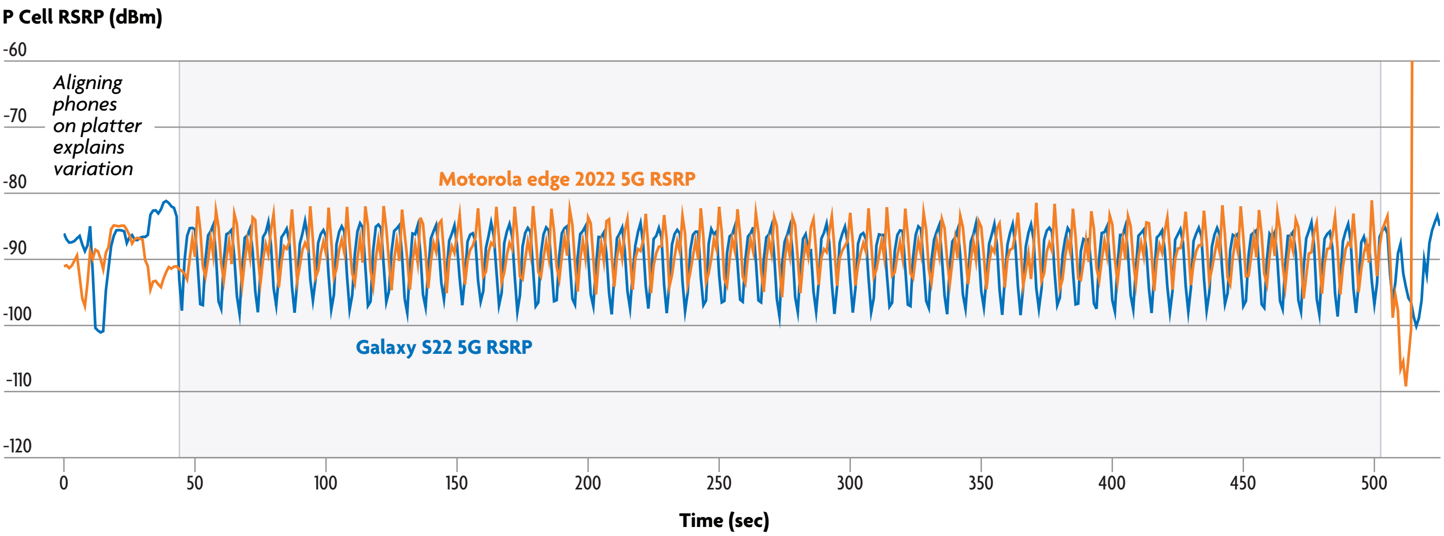




Source: Signals Research Group

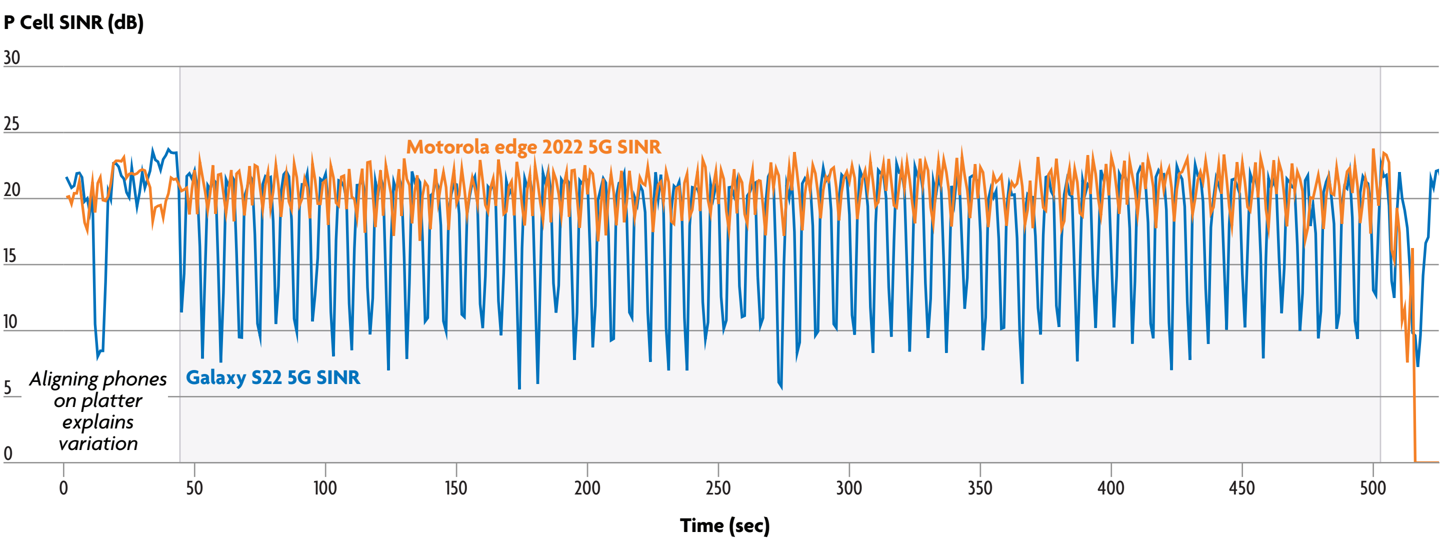
Figure 6 (RSRP and Figure 7 (SINR) shed additional insight into the performance of the two smartphones and their ability to track the best serving beam while rotating on the platter. In the two figures, the absolute values are not as relevant as the differences in variation of the two metrics between the two smartphones. Since the variance in the SINR seems more pronounced than the variance in the throughput for the Galaxy S22, we can infer that differences in chipset optimization strategies played a factor. Although throughput and MCS may be a better metric to evaluate performance, the figure does highlight that the smartphones were experiencing and trying to adjust to constant changes in the RF environment.

Figure 6. Motorola edge 2022 and Samsung Galaxy S22 Primary Cell RSRP Measurements



Source: Signals Research Group

Figure 7. Motorola edge 2022 and Samsung Galaxy S22 Primary Cell SINR Measurements

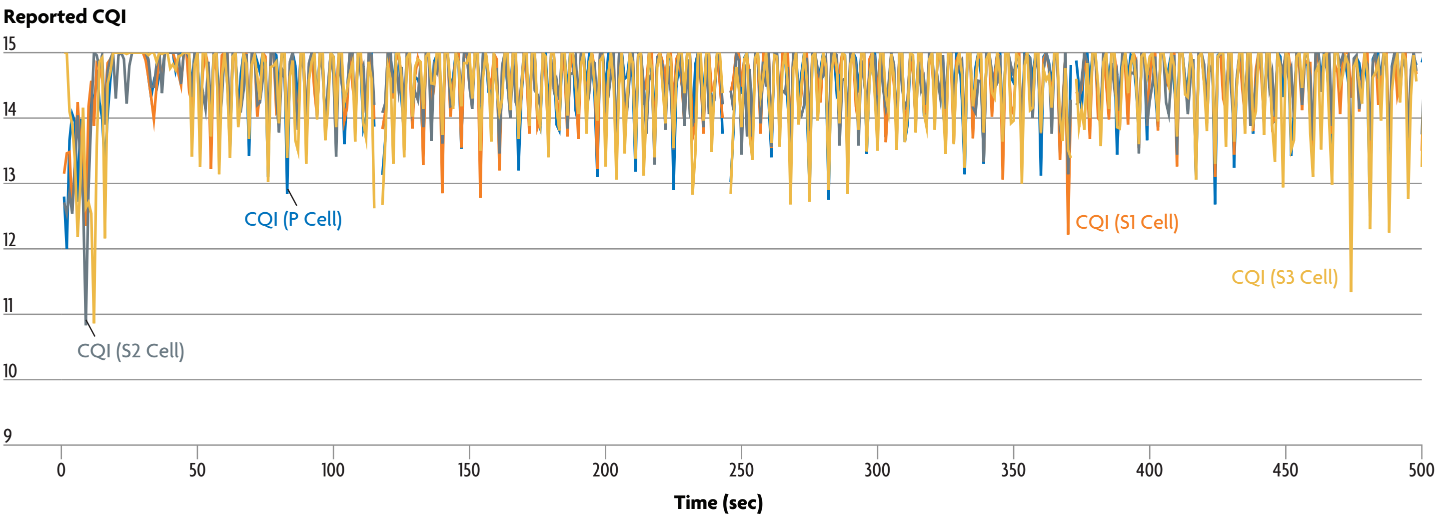


Source: Signals Research Group

The variation shown in Figure 6 and Figure 7, especially for SINR, helps explain the next two figures, which show the CQI (Channel Quality Indicator) reported by the two smartphones during the test. In this case, we are including values for each of the four 100 MHz channels, including the primary cell and the three secondary cells. The figures show much higher variability in the CQI reports for the Galaxy S22 than for the edge 2022. Although the Galaxy S22 CQI peaks at CQI = 14 versus CQI=15 for the edge 2022, we do not believe this point is material since it merely reflects different optimization strategies between the two chipsets. The differences in the variability for the CQI, however, is material and a contributing factor to the differences in throughput and MCS shown in the earlier figures.

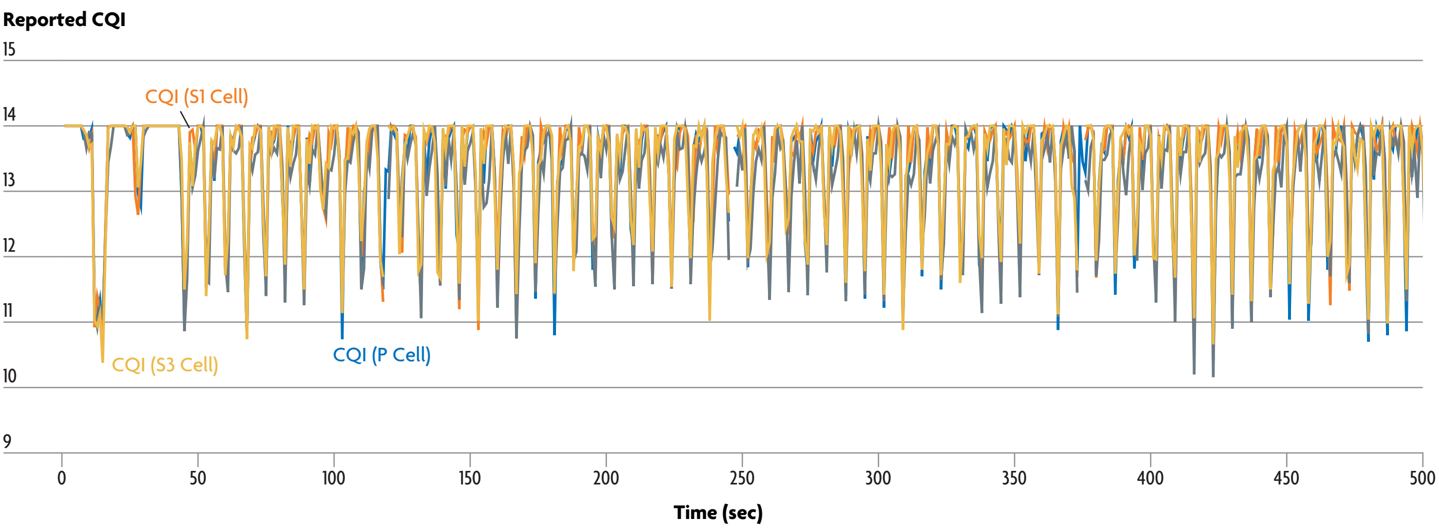
The differences in the variability for the CQI, is a primary reason for the differences in throughput and MCS shown in the earlier figures.

Figure 8. Motorola edge 2022 Primary and Secondary Cells CQI Reports



Source: Signals Research Group

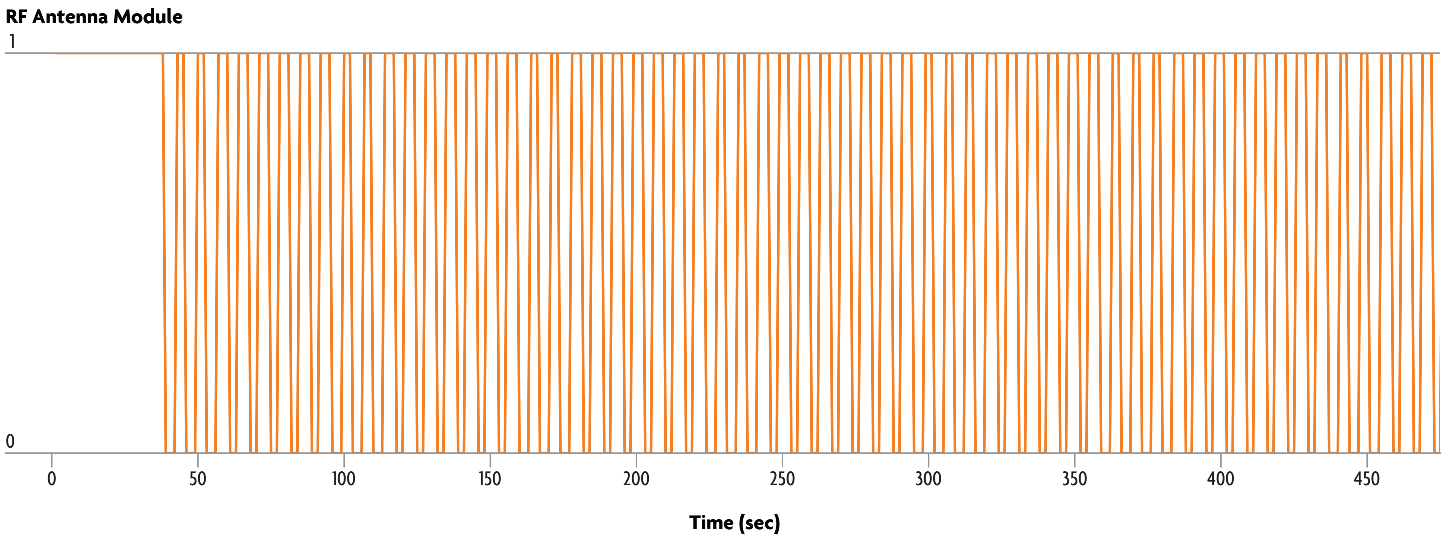
Figure 9. Samsung Galaxy S22 Primary and Secondary Cells CQI Reports



Source: Signals Research Group

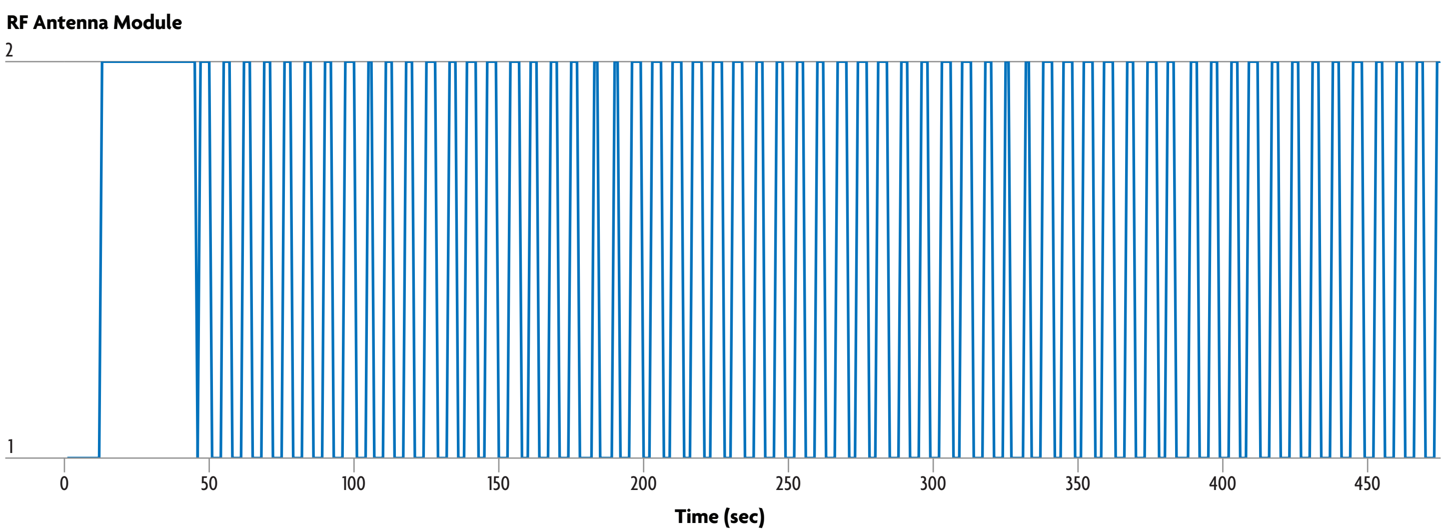
With 5G mmWave, smartphones/chipsets must adjust how they receive and process the mmWave signal to ensure they leverage the best possible signal available. Today's 5G mmWave smartphones generally have at least two RF modules placed at different strategic locations within the smartphone. Depending on how the mmWave signals hit the smartphone, the 5G modem will determine which RF module is better situated to receive and process the signal. The next two figures show how the Motorola smartphone (Figure 10) and the Samsung smartphone (Figure 11) dynamically switched between the two RF modules while the smartphones were rotating on the platter. This information is more interesting when contrasted to their behavior while stationary, which we cover in the next section.

Figure 10. Motorola edge 2022 RF Module Use



Source: Signals Research Group

Figure 11. Samsung Galaxy S22 RF Module Use



Source: Signals Research Group

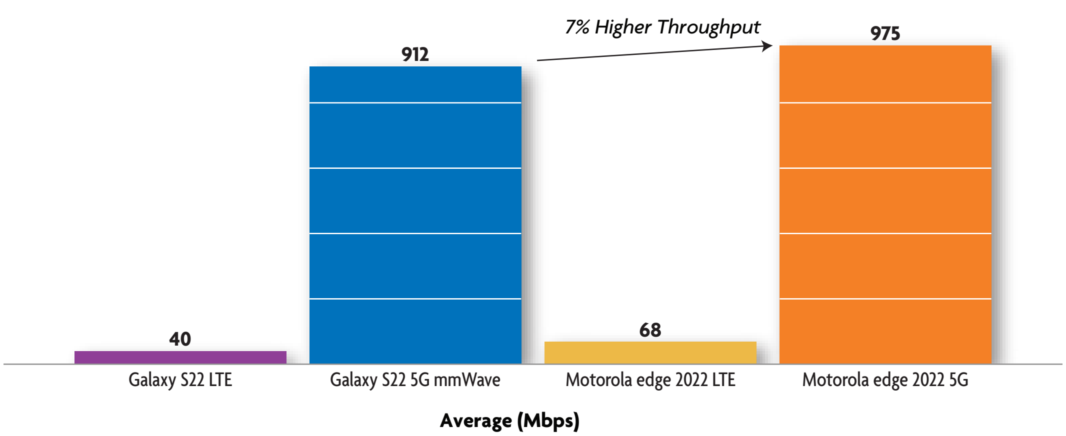
We note there is an additional level of granularity whereby the 5G chipset modems select the best receive beam index to use within each RF module. This information is reported by the Qualcomm chipset, but it wasn't readily available for the MediaTek chipset with our logging tools. Therefore, we went with the common denominator and just showed how the two smartphones/chipsets switched between the two RF modules.

3.2 Motorola edge 2022 and Samsung Galaxy S22 – Stationary Tests

We returned to this test location a few days later to repeat the same test between the Motorola edge 2022 and the Samsung Galaxy S22, with the critical difference being that the platter wasn't rotating during this test. We did this test to demonstrate the performance differences of these smartphones when rotating versus stationary. Among other things, the results of this study clearly demonstrate the high variability in the Galaxy S22 smartphone's performance was entirely due to the rotations and not to other factors.

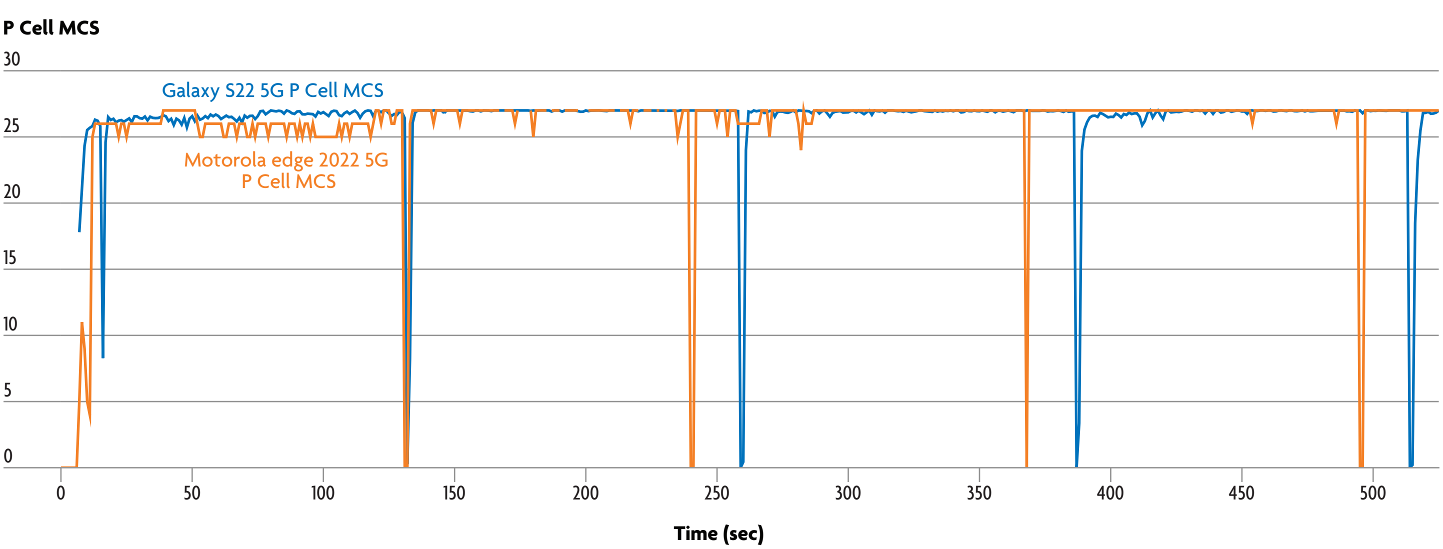
Figure 12 shows the average physical layer throughput for the two smartphones. LTE accounted for 4% (S22) to 7% (edge 2022) of the total throughput. The Motorola edge 2022 achieved higher throughput but since we tested from a single stationary position, the results are not definitive since differences in the placement of the RF modules on the two phones could have had some impact on the results.

Figure 12. Motorola edge 2022 and Samsung Galaxy S22 Physical Layer Throughput



Source: Signals Research Group

Figure 13. Motorola edge 2022 and Samsung Galaxy S22 Primary Cell MCS Values

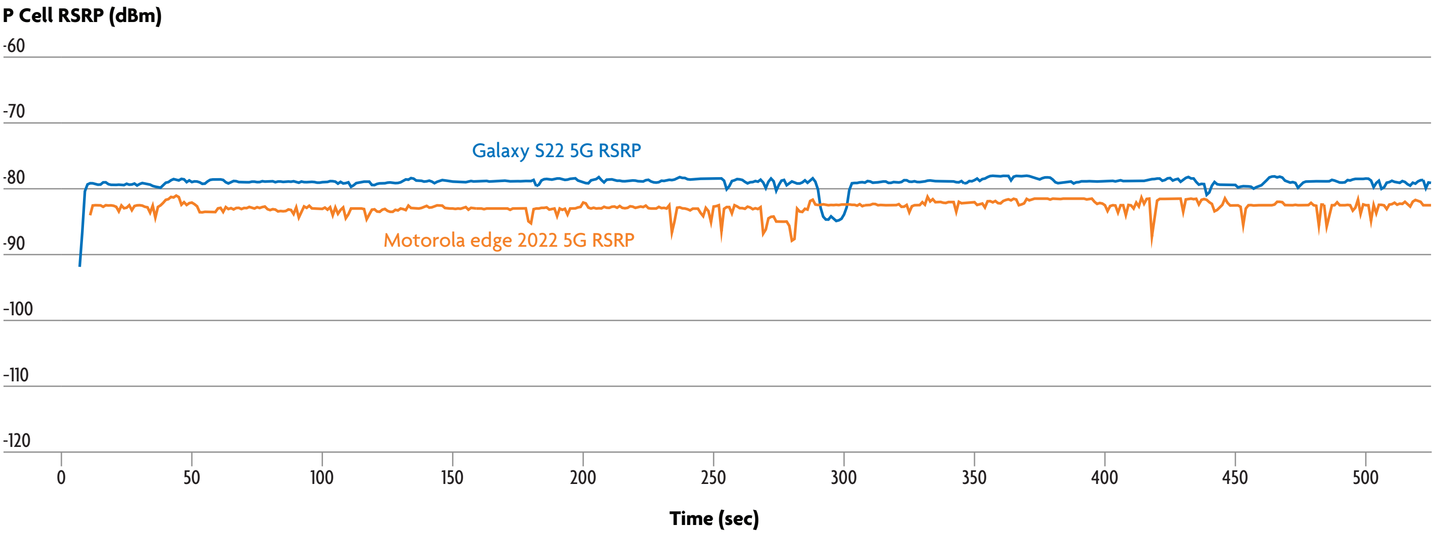


Source: Signals Research Group

The more compelling information appears in the next several figures. Figure 13 shows the reported MCS values used by the two smartphones during the test. Unlike what occurred during the rotating test (Figure 5), there were inconsequential variations in the reported MCS values for both smartphones. The only dips coincided with the end of each Umetrix data session. Likewise, Figure 14 (RSRP) and Figure 15 (SINR) show how the RSRP and SINR remained largely unchanged during the stationary test. These results are much different from what we showed in the previous section, in particular for the Galaxy S22 smartphone.

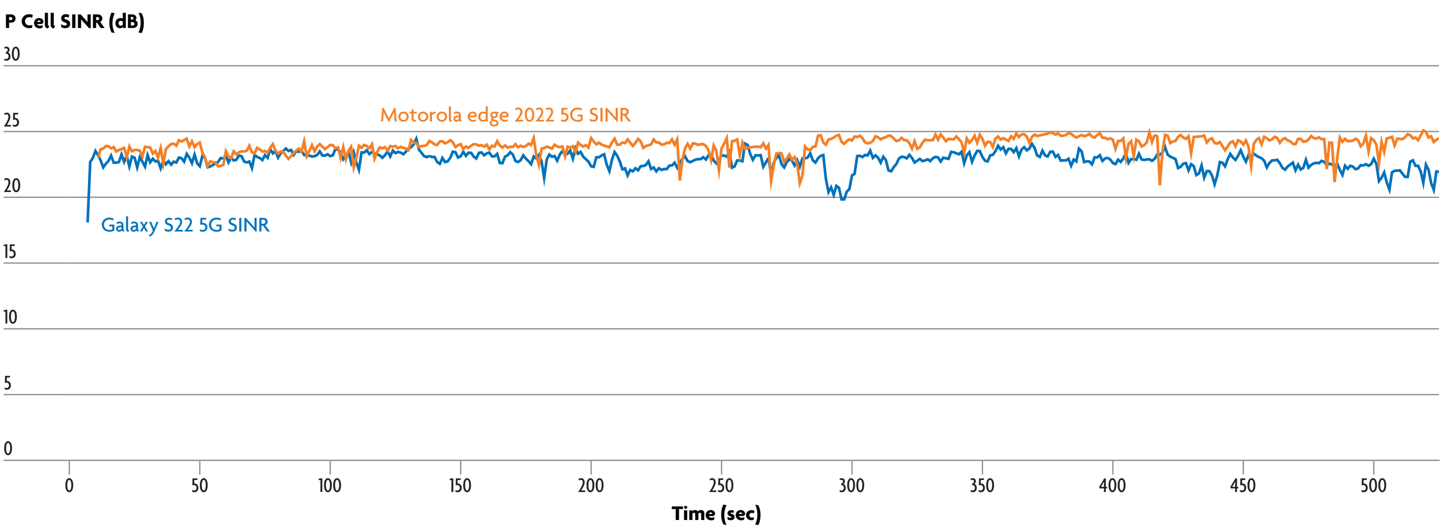
Without rotation, the two smartphones had inconsequential variations in their reported MCS values and only modest variations in their reported RSRP and SINR.

Figure 14. Motorola edge 2022 and Samsung Galaxy S22 Primary Cell RSRP Measurements



Source: Signals Research Group

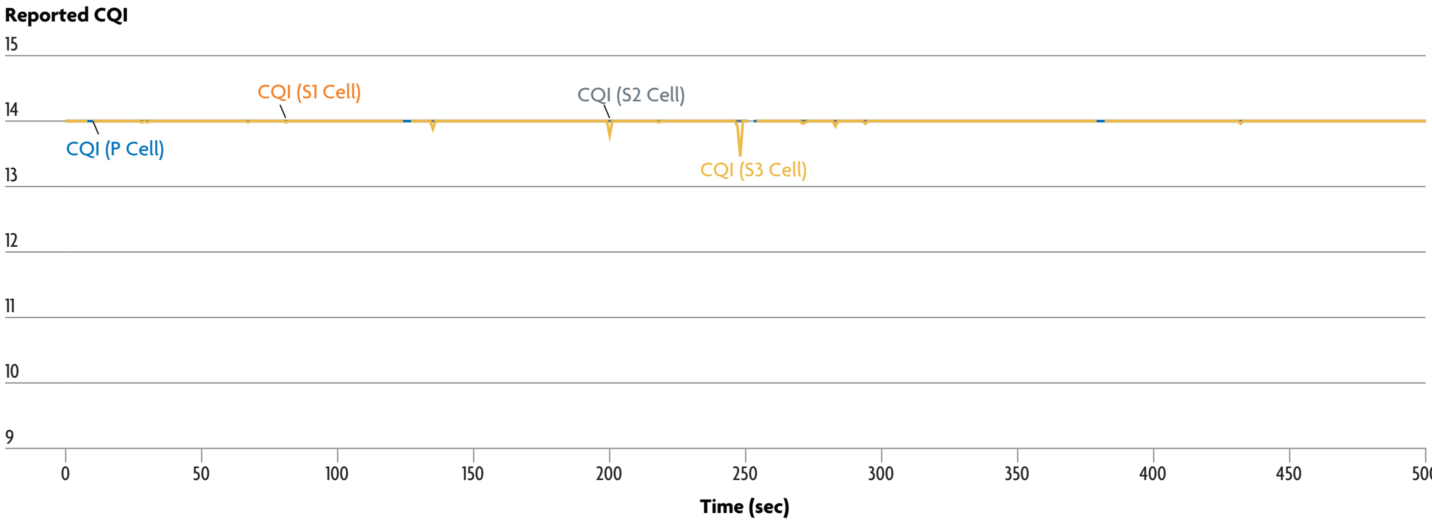
Figure 15. Motorola edge 2022 and Samsung Galaxy S22 Primary Cell SINR Measurements



Source: Signals Research Group

Figure 16 shows very consistent CQI reports on all four carriers for the Galaxy S22, which is a sharp contrast from what is found in Figure 9. It seems logical to conclude that both smartphones did a better job of tracking/leveraging the best beam while stationary than while rotating, just as it is evident the Motorola edge 2022 smartphone did a much better job of tracking/leveraging the best beam while rotating than the Samsung Galaxy S22.

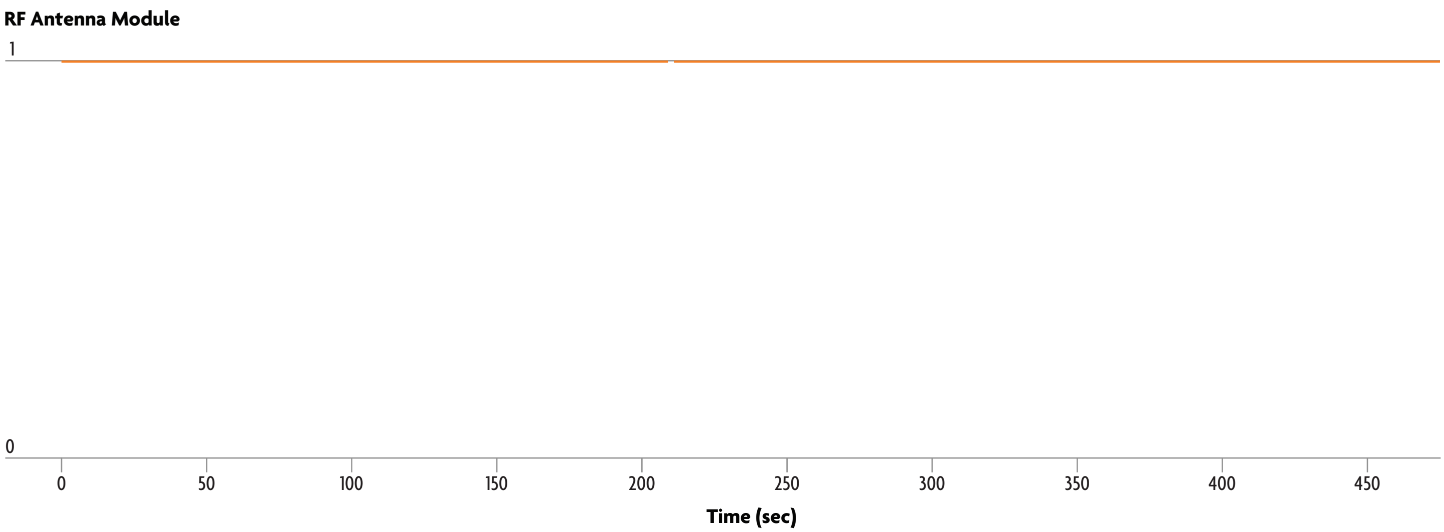
Figure 16. Samsung Galaxy S22 Primary and Secondary Cells CQI Reports



Source: Signals Research Group

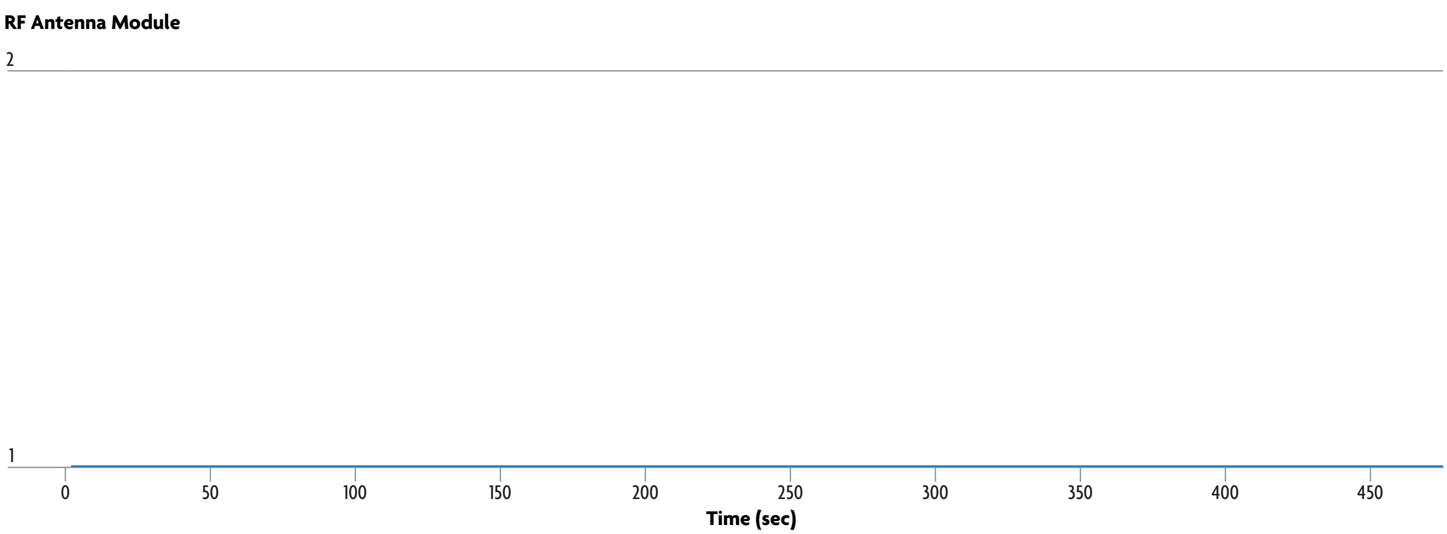
Lastly, since the smartphones were stationary on the platter, both phones used the same RF module throughout the entire test. There may have been adjustments with how the two chipsets leveraged different beam indices within their respective RF modules, but we weren't able to collect this level of detail with the Motorola edge 2022 smartphone, so we elected to exclude it for both smartphones.

Figure 17. Motorola edge 2022 RF Module Use



Source: Signals Research Group

Figure 18. Samsung Galaxy S22 RF Module Use



Source: Signals Research Group

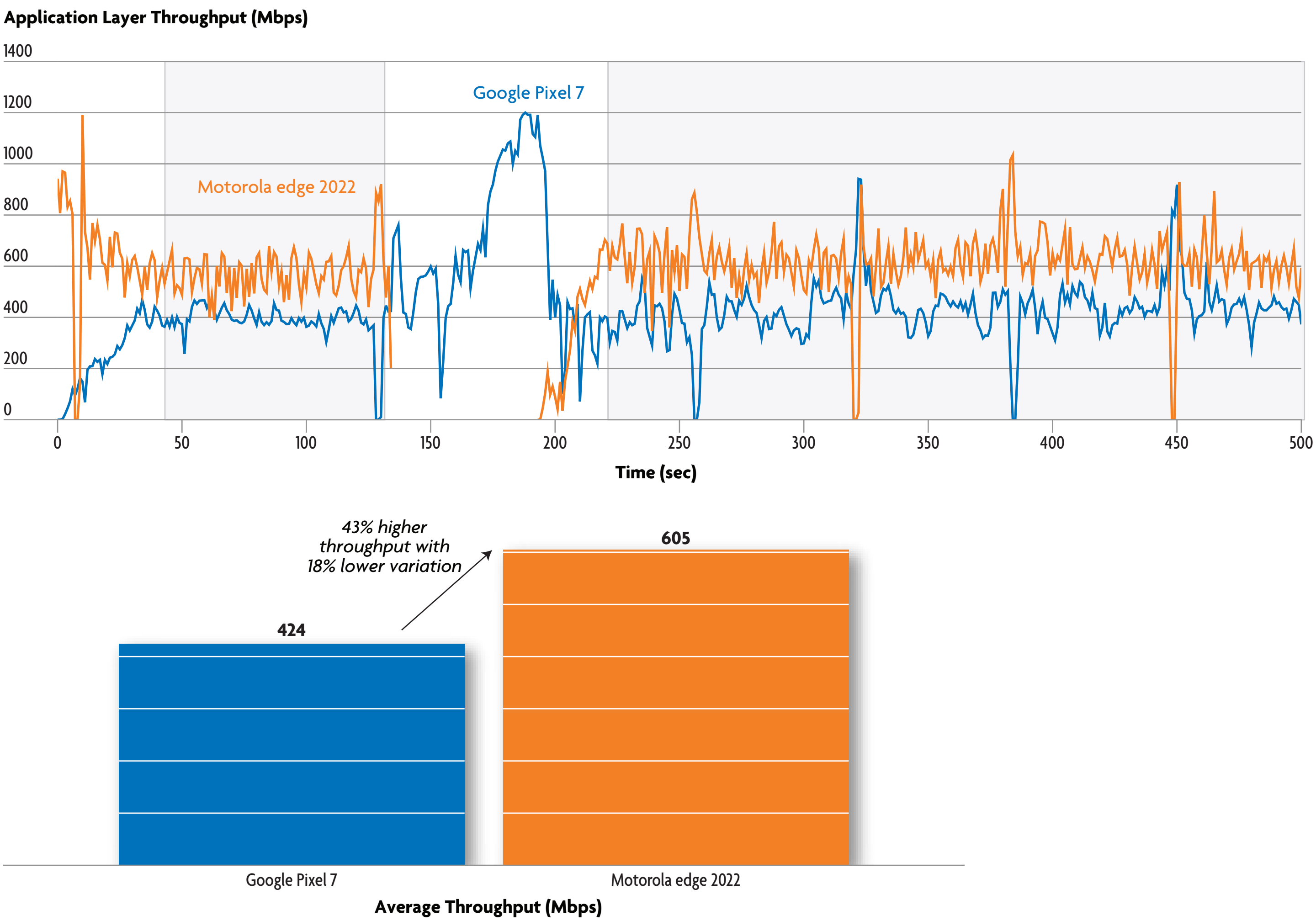
3.3 Motorola edge 2022 and Google Pixel 7

We don't have physical layer information for the Google Pixel 7 since it wasn't possible for us to expose the diagnostic port on this smartphone without the support of the handset manufacturer. We can, however, leverage application layer results for both smartphones and our observation from the previous two sections that LTE only comprised a modest percentage of the total throughput. Likewise, we still had access to physical layer results for the Motorola edge 2022 in this test so to the extent there were any anomalies in the application layer results, we could turn to the physical layer results for additional insight. We also note that we can leverage edge 2022 physical layer information to infer how the Pixel 7 was interacting with the 5G mmWave network. For example, we can look at RB allocations for the Motorola edge 2022 smartphone to infer how the network was scheduling the Pixel 7.

For this test the Umetrix data session didn't restart on the Motorola edge 2022 smartphone after the first iteration, so we excluded the results between approximately 125 seconds and 200 seconds. Based on the information in the figure, the Motorola edge 2022 smartphone achieved 43% higher throughput with 18% lower variation.

The Motorola edge 2022 smartphone achieved 43% higher throughput with 18% lower variation.

Figure 19. Motorola edge 2022 and Google Pixel 7 Application Layer Throughput



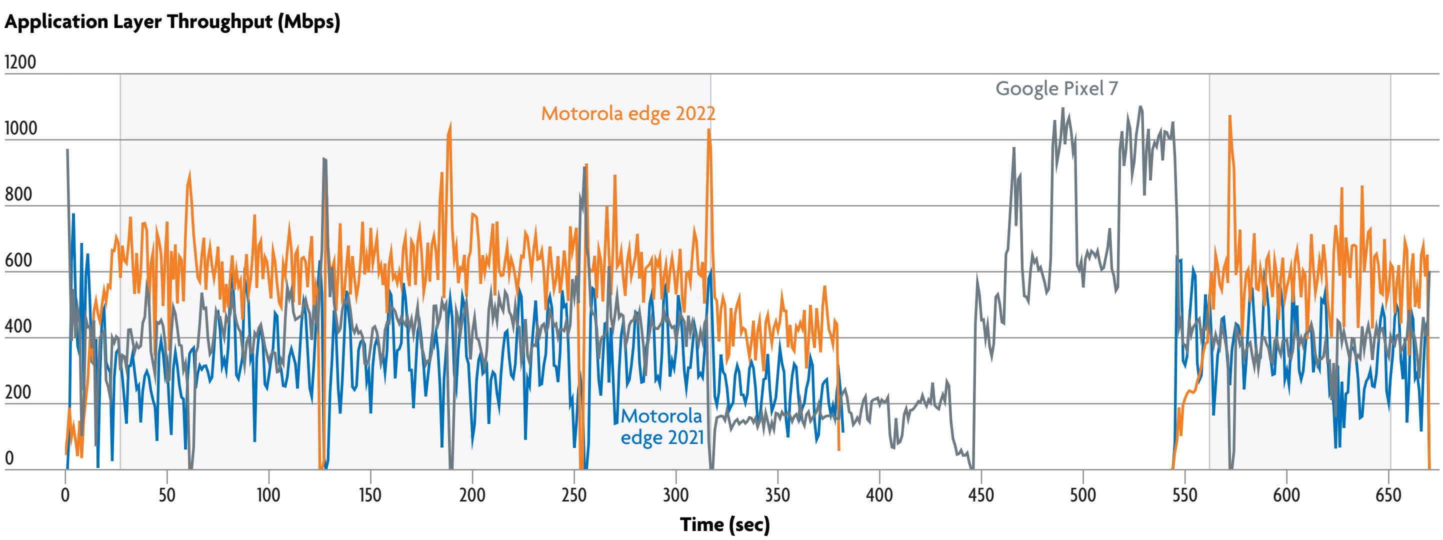
Source: Signals Research Group

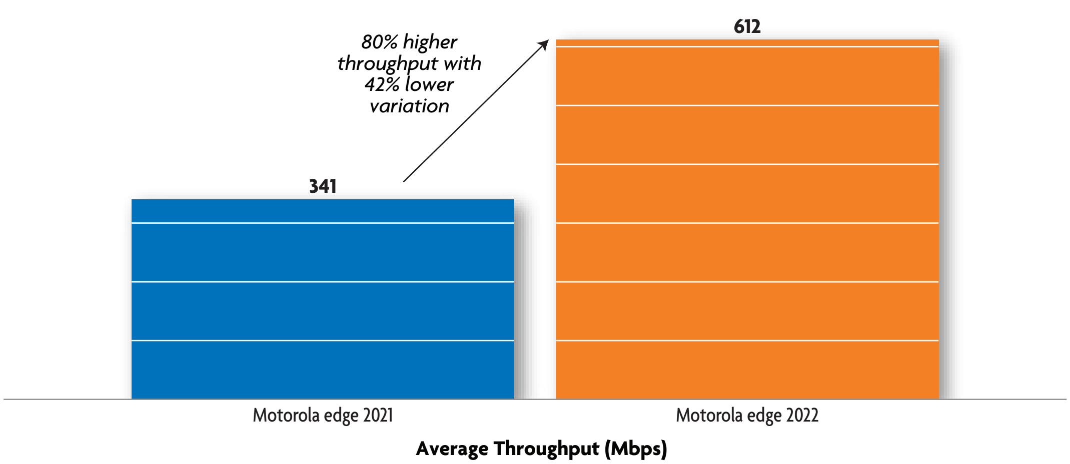
3.4 Motorola edge 2022 and Motorola edge 2021

Figure 20 shows the results involving side by side testing of the Motorola edge 2022 and Motorola edge 2021 smartphones. During this test, we inadvertently left Umetrix running on the Google Pixel smartphone, which was lying face down on the test vehicle. Therefore, for full transparency we are including the application throughput for all three phones in Figure 20. This action, which we will blame on the very cold weather impacting the blood flow to our brain, reduced the overall throughput of the other two phones, but it had no impact on the relative performance between the two Motorola smartphones. We can't completely explain the lower throughput between 325 and 375 seconds in the test, but it impacted the throughput for the two phones under test, as well as the Google Pixel 7. The drop in the throughput for all smartphones corresponded with the Google Pixel 7 data transfer and it recovered at the start of the next data cycle when the Pixel 7 was running by itself. Based on our analysis of the results for the two highlighted regions in the figure, the Motorola edge 2022 smart-phone achieved 80% higher throughput with 42% lower variation, compared with the Motorola edge 2021 smartphone.

The Motorola edge 2022 smartphone achieved 80% higher throughput with 42% lower variation, compared with the Motorola edge 2021 smartphone.

Figure 20. Motorola edge 2022 and Motorola edge 2021 Application Layer Throughput

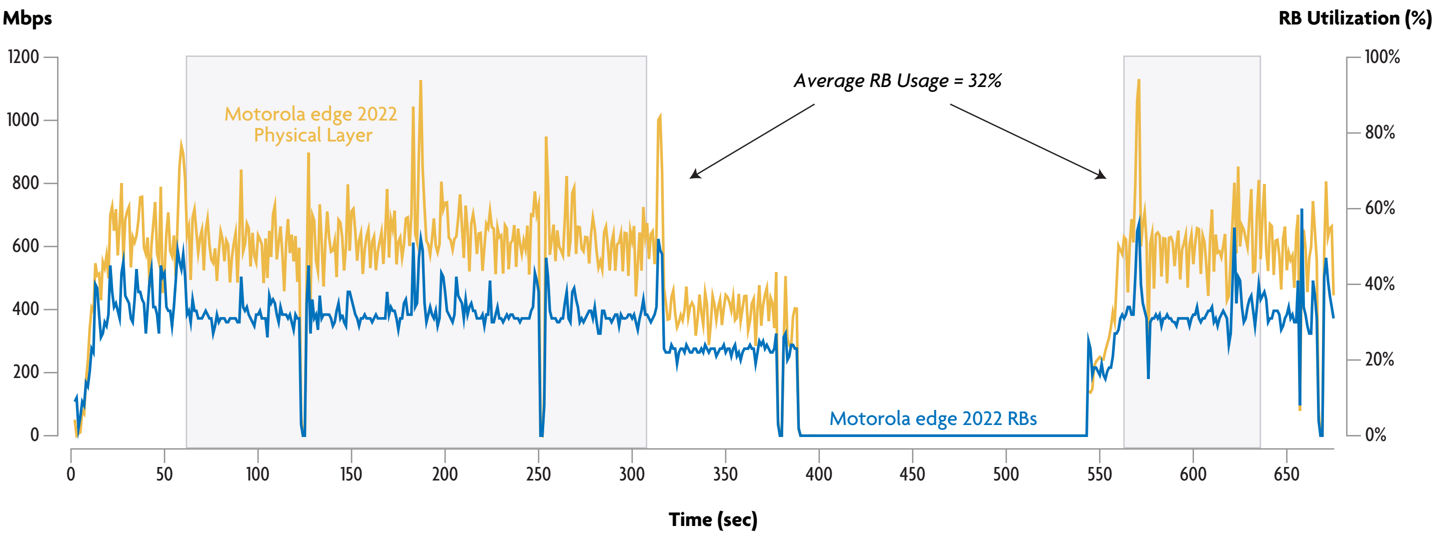




Source: Signals Research Group

As a sanity check, we looked at the PDSCH RB usage for the Motorola edge 2022 smartphone. As shown in Figure 21, the physical layer throughput tracked nicely with the application layer throughput shown in the previous figure. More importantly, the smartphone's RB usage was 32%, strongly indicating the network scheduler was equally allocating network resources between the three smartphones during the highlighted regions.

Figure 21. Motorola edge 2022 Physical Layer Throughput and Total RB Usage



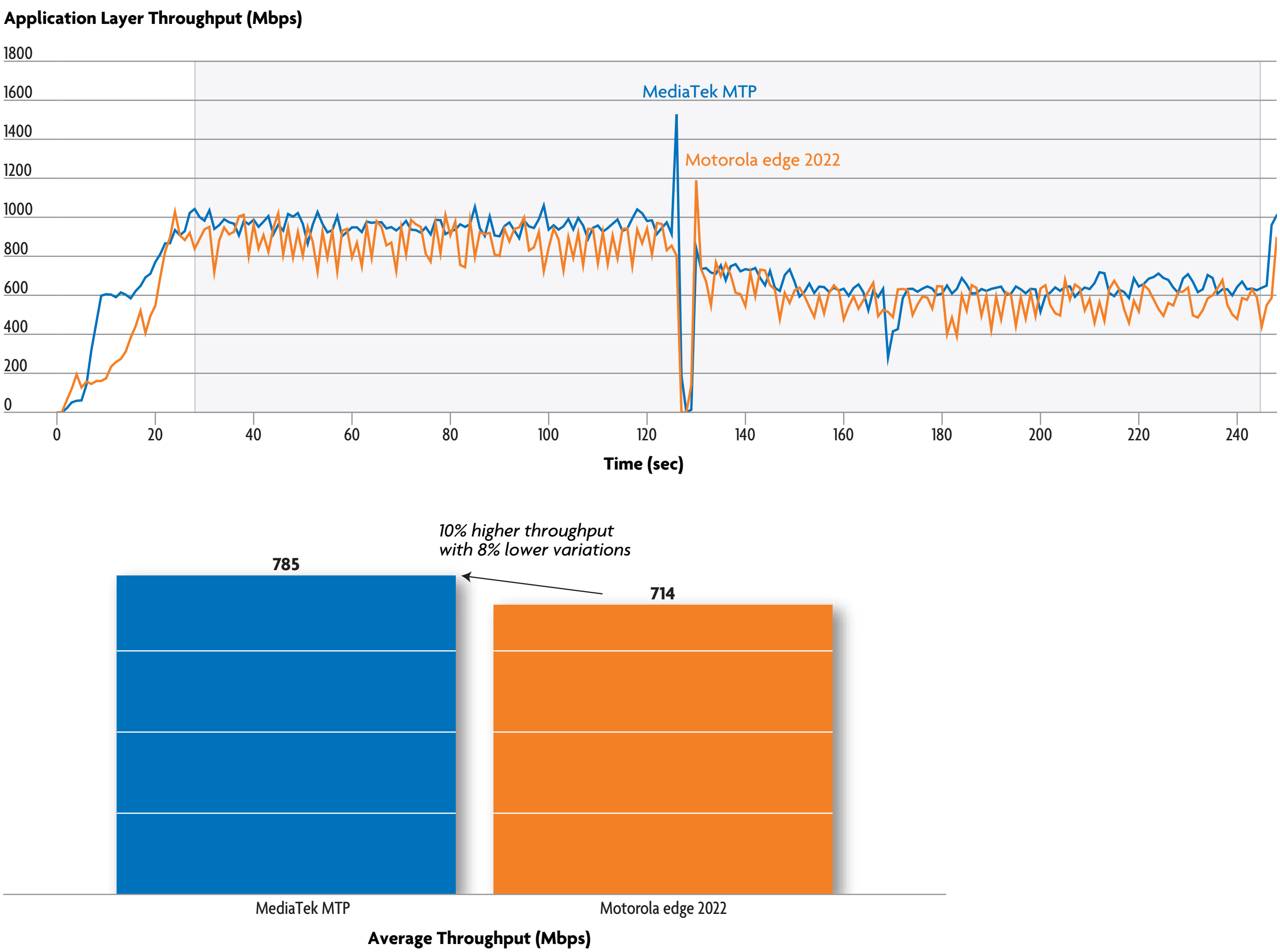
Source: Signals Research Group

Given the large gap in performance between the two smartphones, we repeated the test between these two pairs of phones after we had finished testing the other combinations. For this test, we swapped the SIM card in the edge 2021 smartphone. Although we had unlimited data plans with no throttling, we wanted to confirm there wasn't some sort of provisioning issue taking place. The results from this test were consistent with what we included in this report.

3.5 Motorola edge 2022 and MediaTek Mobile Test Platform

Figure 22 shows the results from testing the Motorola edge 2022 smartphone and the MediaTek MTP. During the first Umetrix data session, the combined throughput for the two smartphones approached 2 Gbps, but during the second Umetrix data session it was less than 1.2 Gbps. Again, loading from another device in the network could explain the phenomenon. We confirmed none of our smartphones were attached to the network. Based on these results, the MediaTek MTP slightly outperformed the Motorola edge 2022 smartphone, achieving 10% higher throughput with 8% lower variance in the throughput.

Figure 22. Motorola edge 2022 and MediaTek MTP Application Layer Throughput



Source: Signals Research Group

4.0 Location 2 Line-of-Site Test Results

This test location represented nearly ideal conditions, as shown in Figure 23. Since the adjacent road was heavily traveled, larger vehicles could have interfered with the mmWave transmission between the cell site and the two smartphones under test. If this situation occurred, then it would have taken place with both smartphones under test, thus making it a fair comparison.

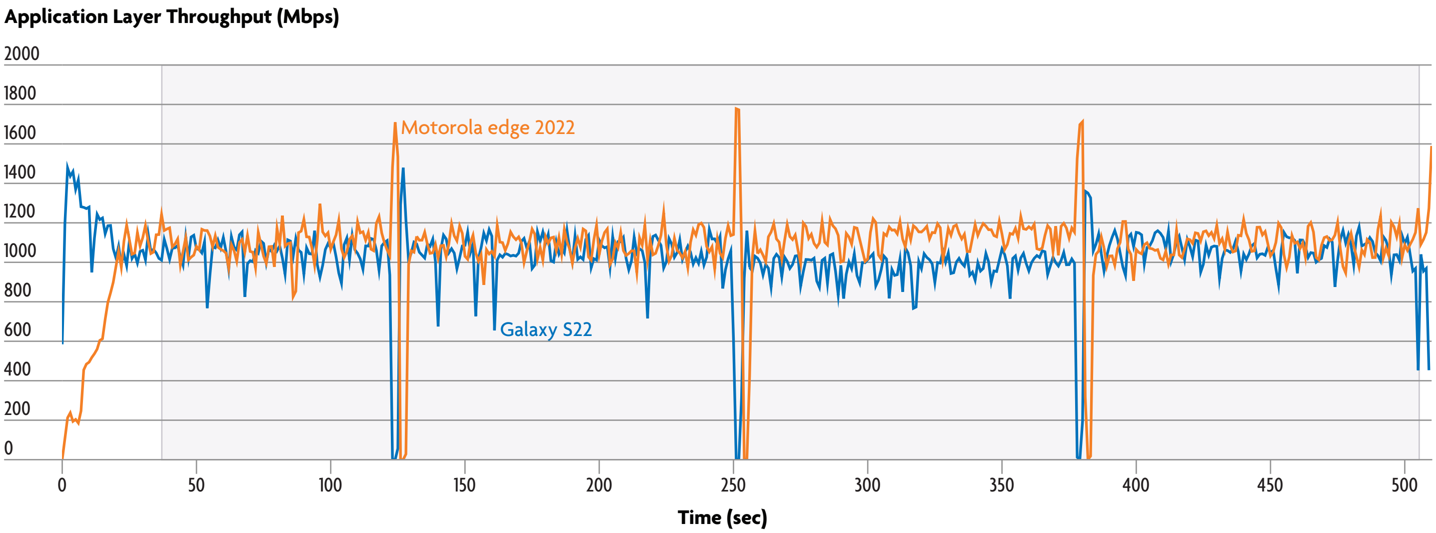
Figure 23. Test Location

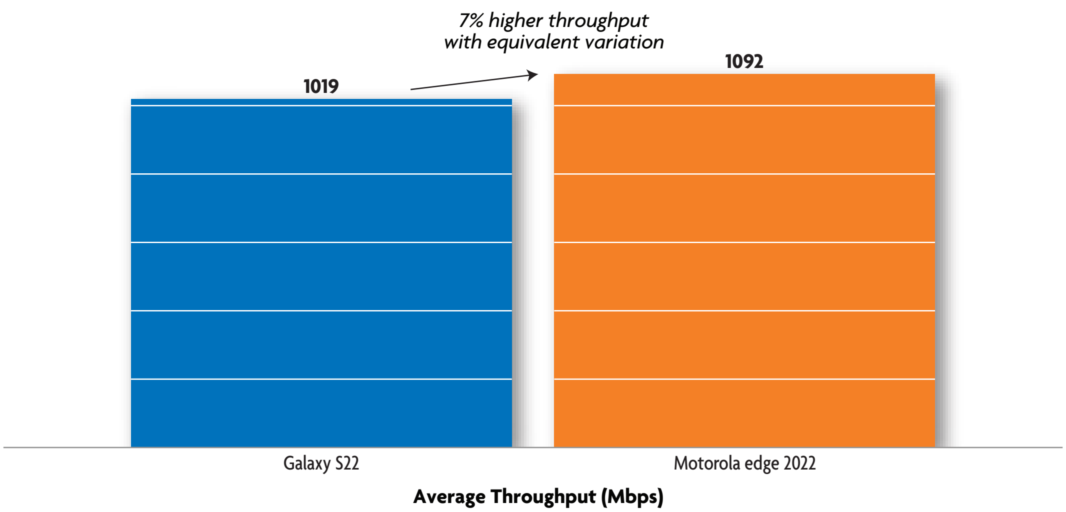
Source: Signals Research Group

4.1 Motorola edge 2022 and Galaxy S22

Given the more ideal RF conditions, the results between the Motorola edge 2022 smartphone and the Samsung Galaxy S22 smartphone were similar. The difference in the application layer throughput was only 7% while the difference was only 6% at the physical layer (5G only), with both outcomes favoring the Motorola edge 2022. The variances in the throughput were equivalent.

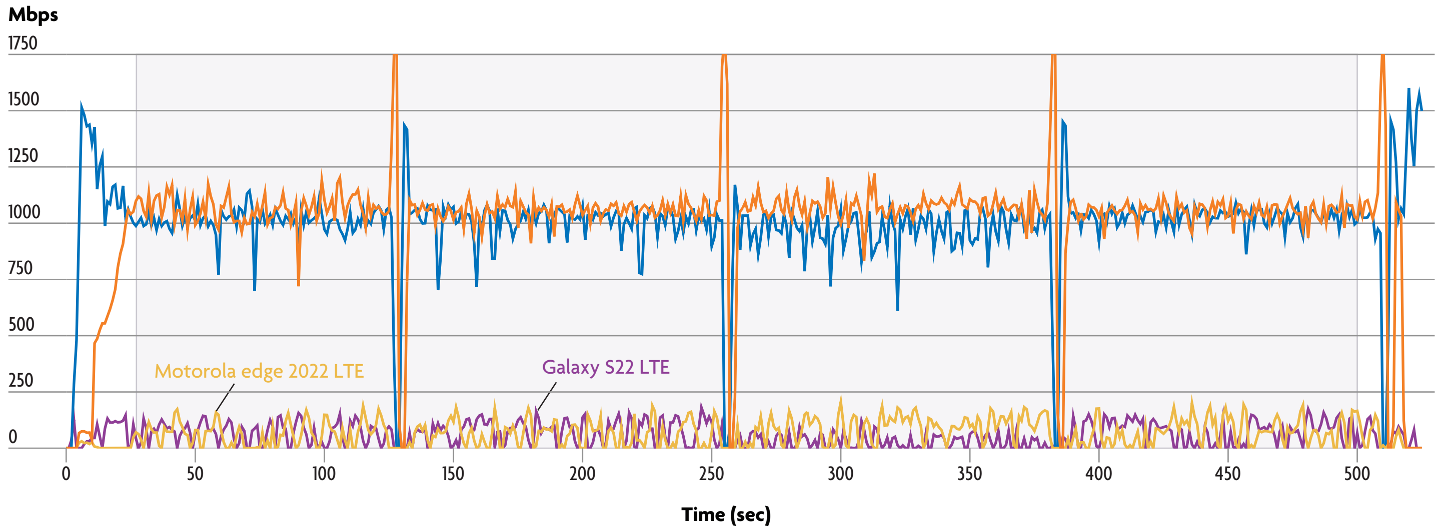
Figure 24. Motorola edge 2022 and Galaxy S22 Application Layer Throughput

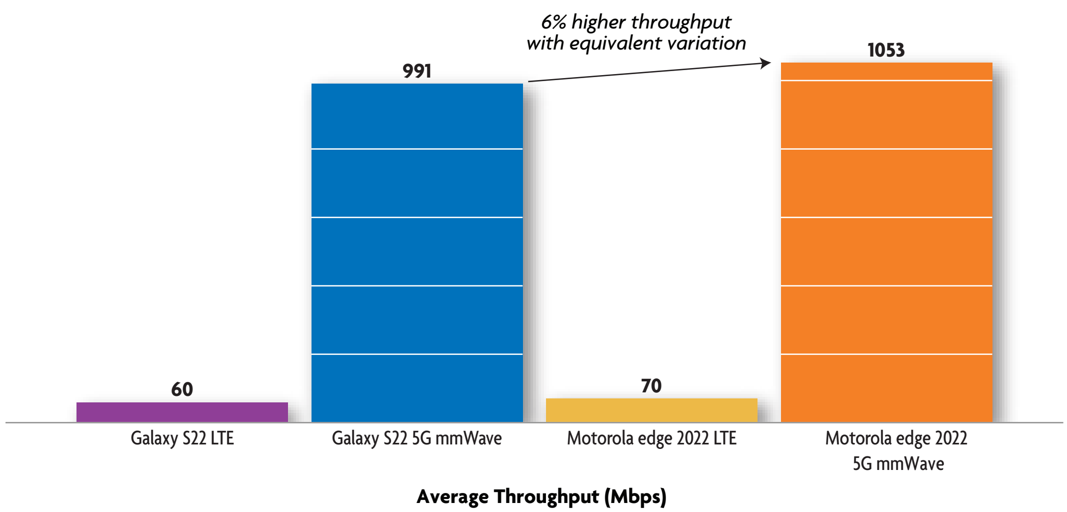




Source: Signals Research Group

Figure 25. Motorola edge 2022 and Galaxy S22 Physical Layer Throughput

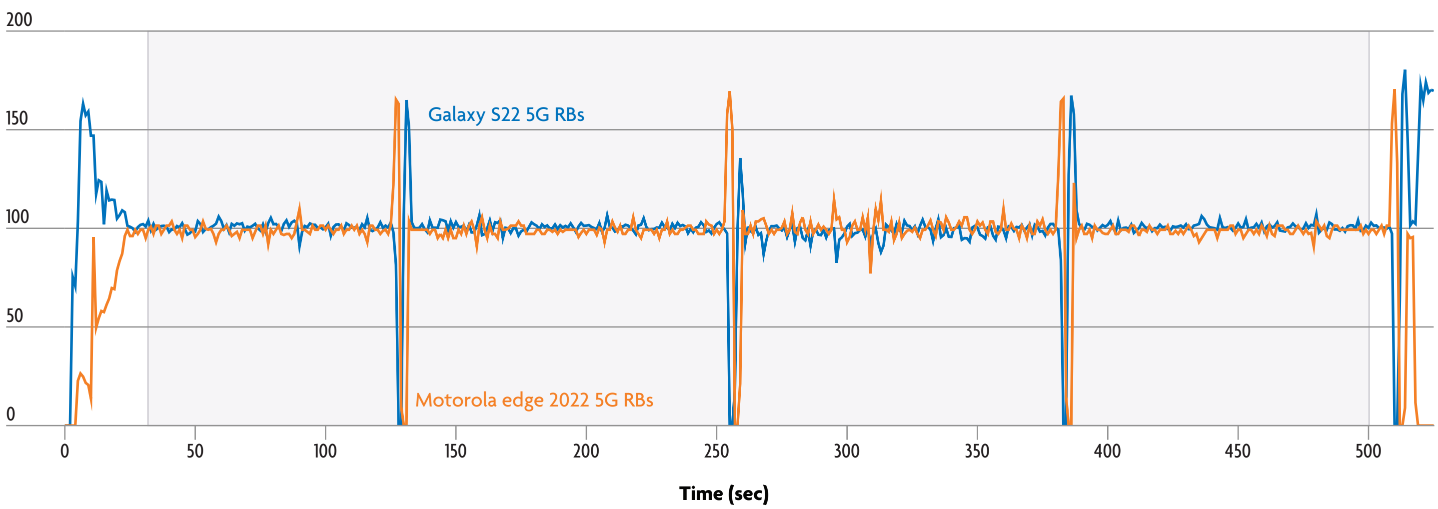


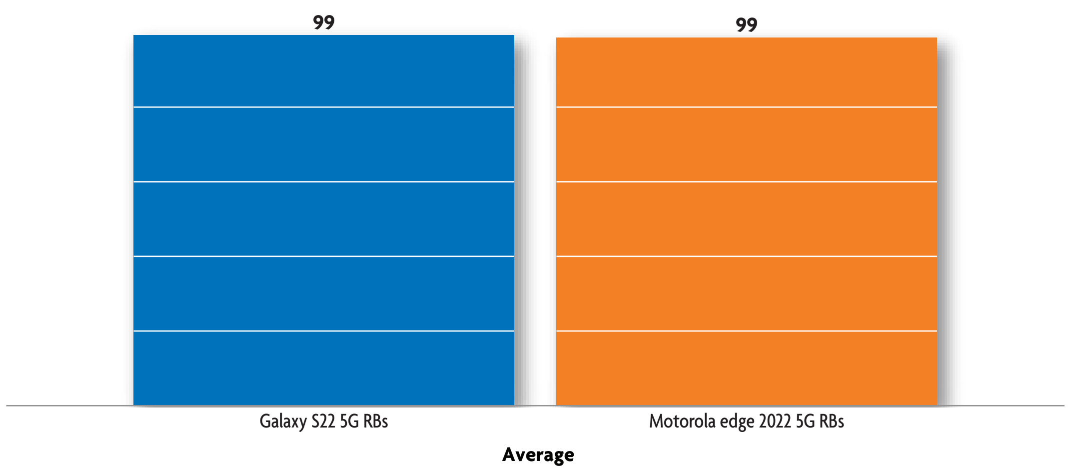


Source: Signals Research Group

As documented in Figure 26 the two smartphones used an equivalent number of network resources.

Figure 26. Motorola edge 2022 and Samsung Galaxy S22 PDSCH Resource Block Allocations

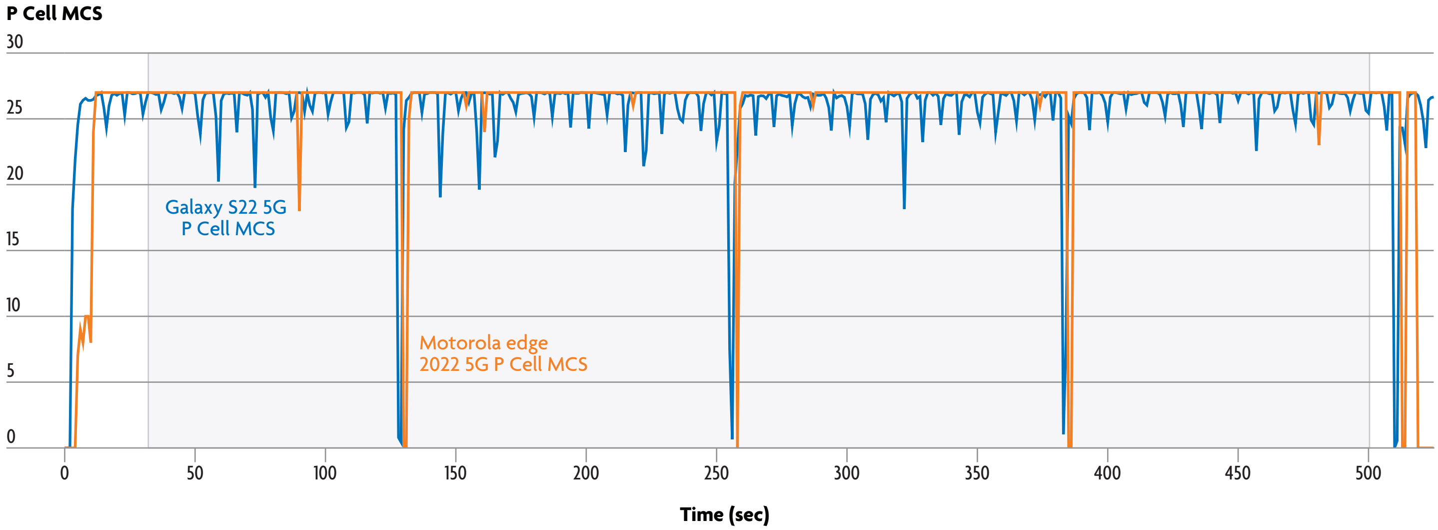


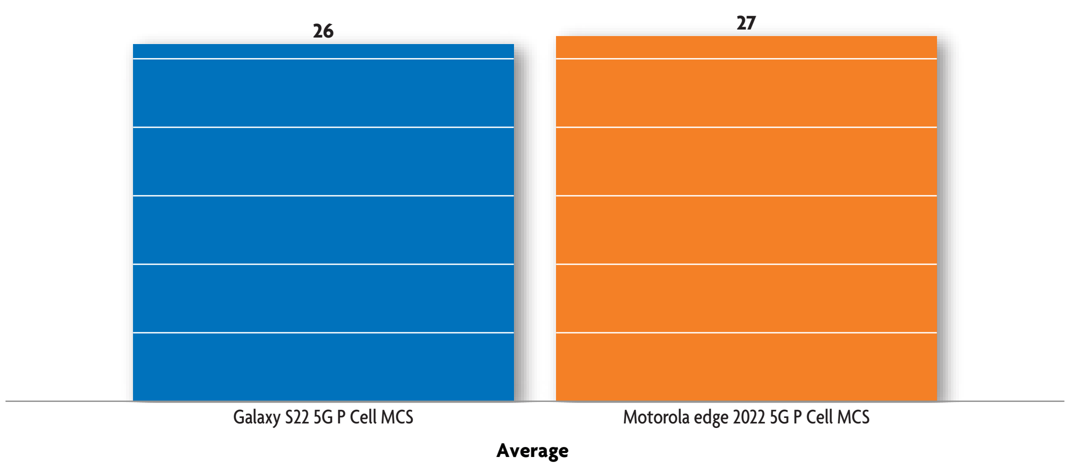


Source: Signals Research Group

There was higher variation in the MCS values for the Galaxy S22 smartphone, as shown in Figure 27. Likewise, the variation in the RSRP (Figure 28) and SINR (Figure 29) were higher with the Galaxy S22.

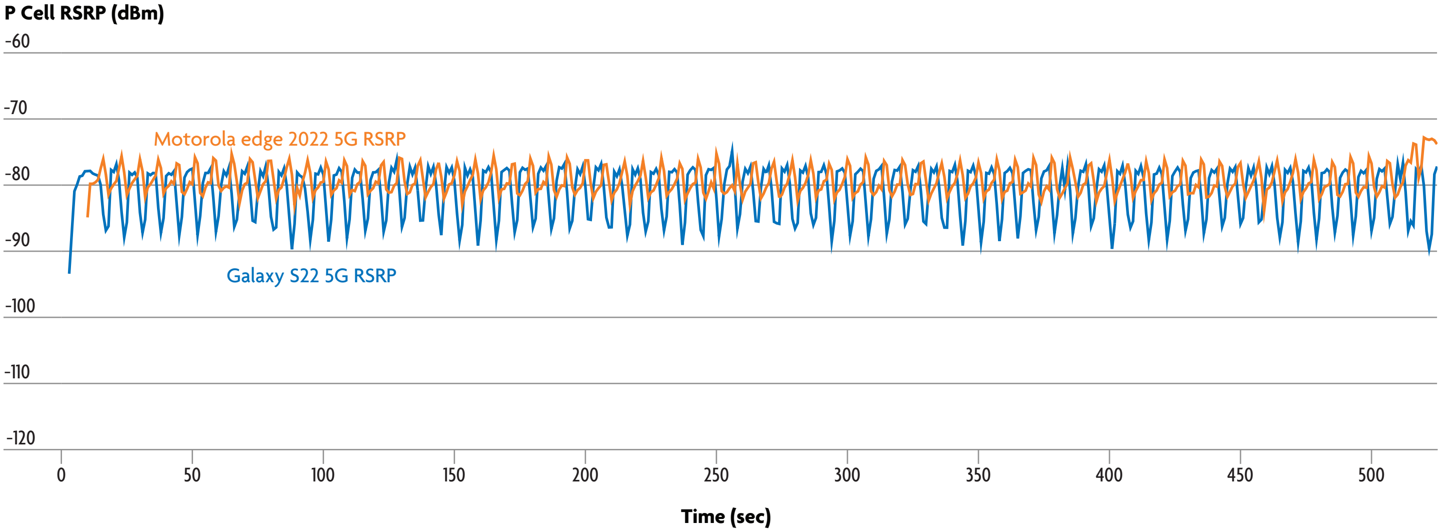
Figure 27. Motorola edge 2022 and Samsung Galaxy S22 Primary Cell MCS Allocations





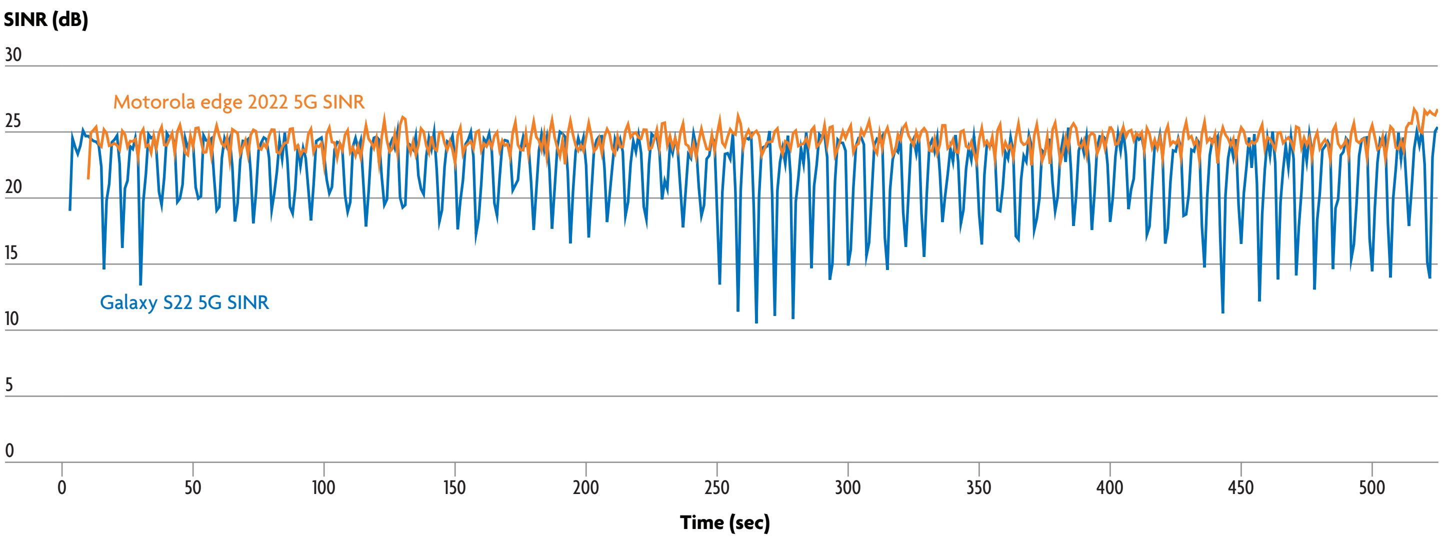
Source: Signals Research Group

Figure 28. Motorola edge 2022 and Samsung Galaxy S22 Primary Cell RSRP Measurements



Source: Signals Research Group

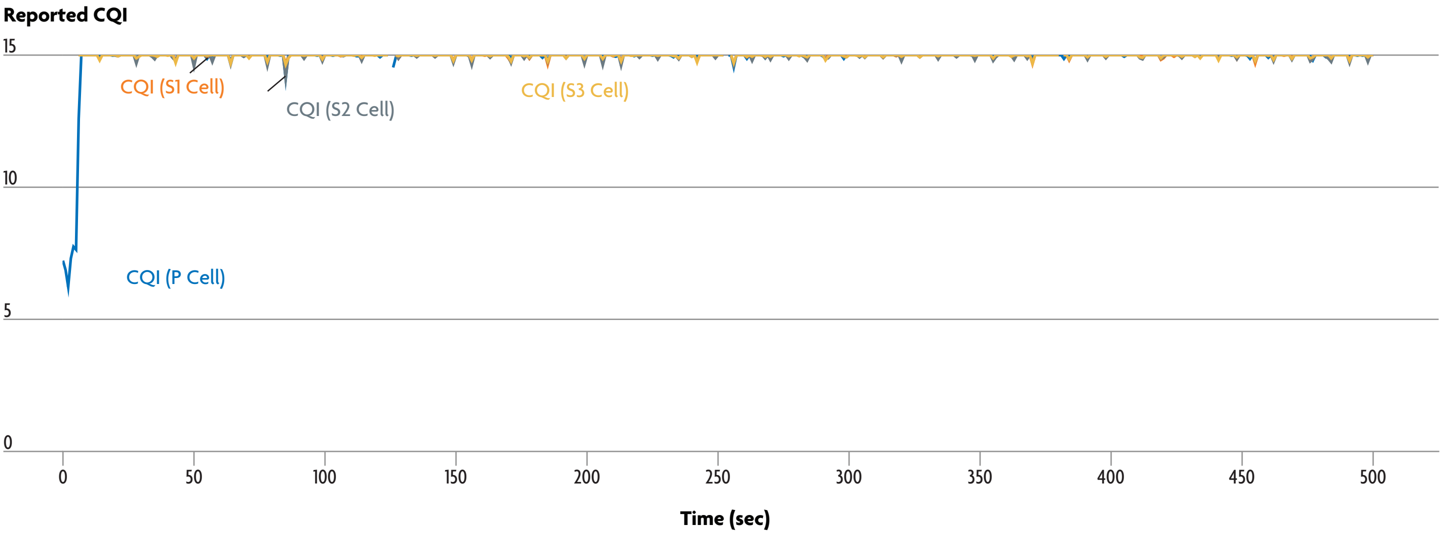
Figure 29. Motorola edge 2022 and Samsung Galaxy S22 Primary Cell SINR Measurements



Source: Signals Research Group

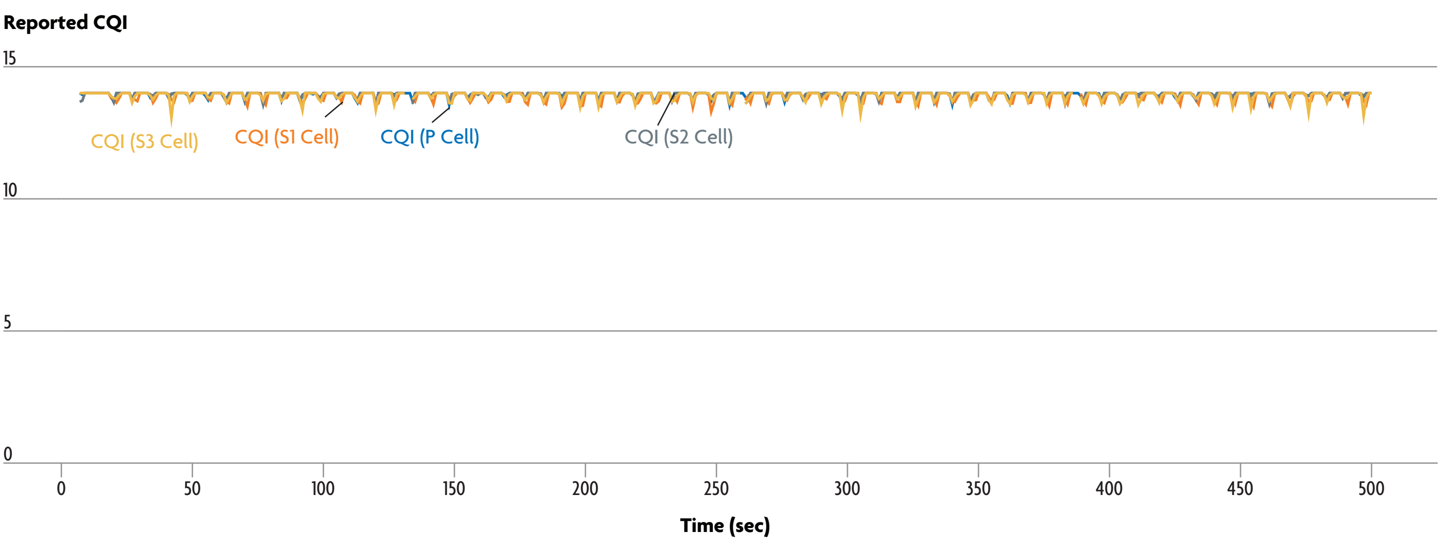
Despite the more apparent differences in the SINR, which could be influenced by differences in how the chipsets measure and report SINR, the average variance in the CQI for the four mmWave channels was below 1% for both smartphones, albeit slightly higher for the Galaxy S22 (0.9%) than for the edge 2022 (0.4%). Once again, the absolute throughput along with their variances are what matter most with the MCS and CQI reports helping to reflect why the variances occurred.

Figure 30. Motorola edge 2022 Primary and Secondary Cells CQI Reports



Source: Signals Research Group

Figure 31. Samsung Galaxy S22 Primary and Secondary Cells CQI Reports

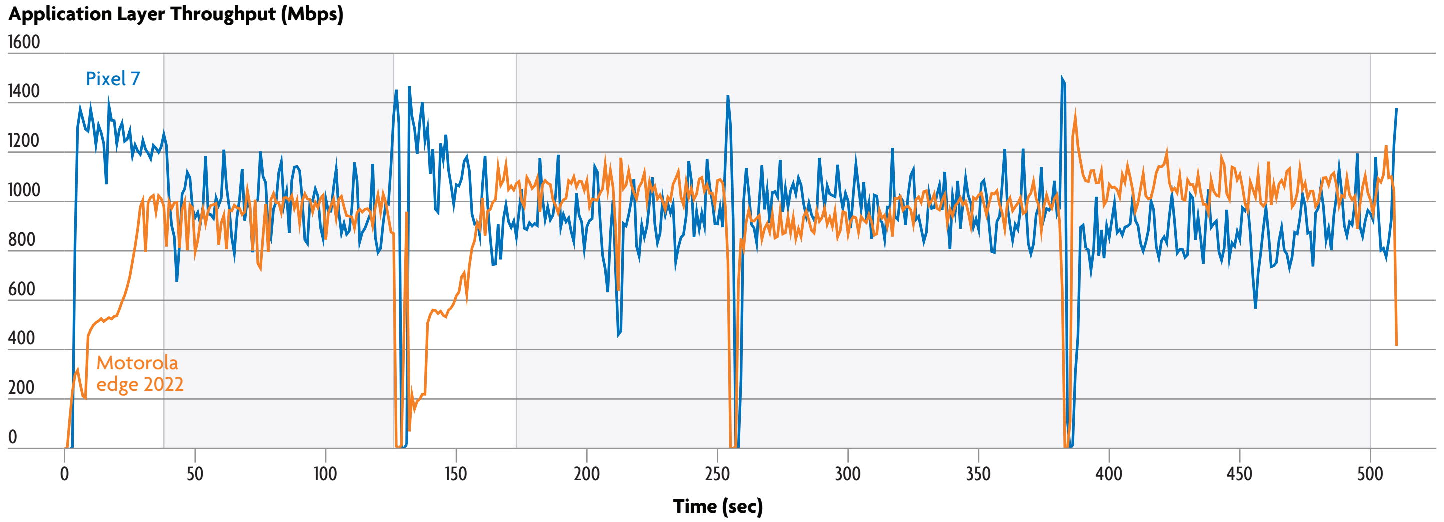


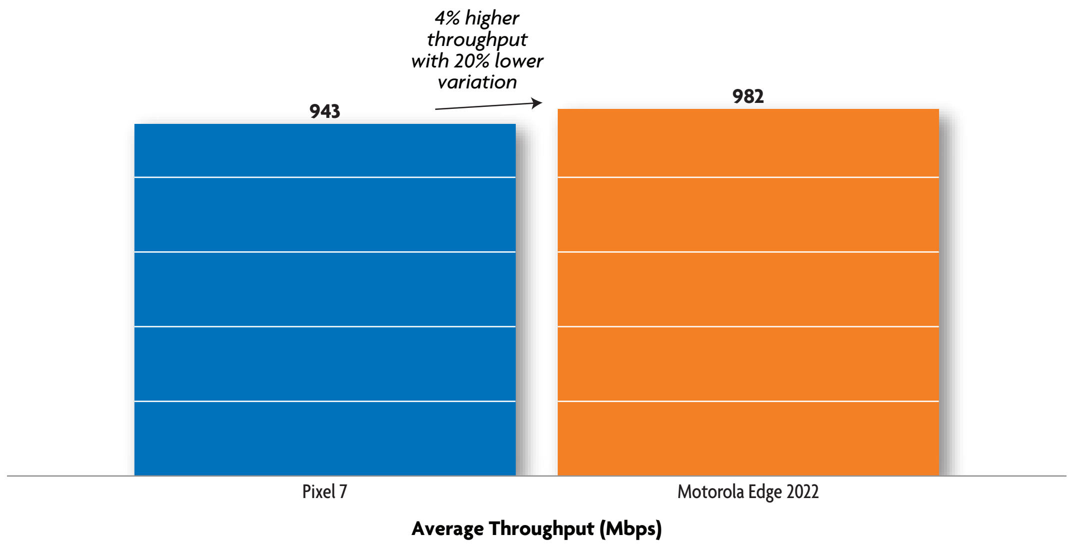
Source: Signals Research Group

4.2 Motorola edge 2022 and Google Pixel 7

The Motorola edge 2022 smartphone only had 4% higher application layer throughput than the Google Pixel 7 at this test location. However, the variation in the throughput for the Motorola smartphone was 20% lower than it was for the Google Pixel.

Figure 32. Motorola edge 2022 and Google Pixel 7 Application Layer Throughput



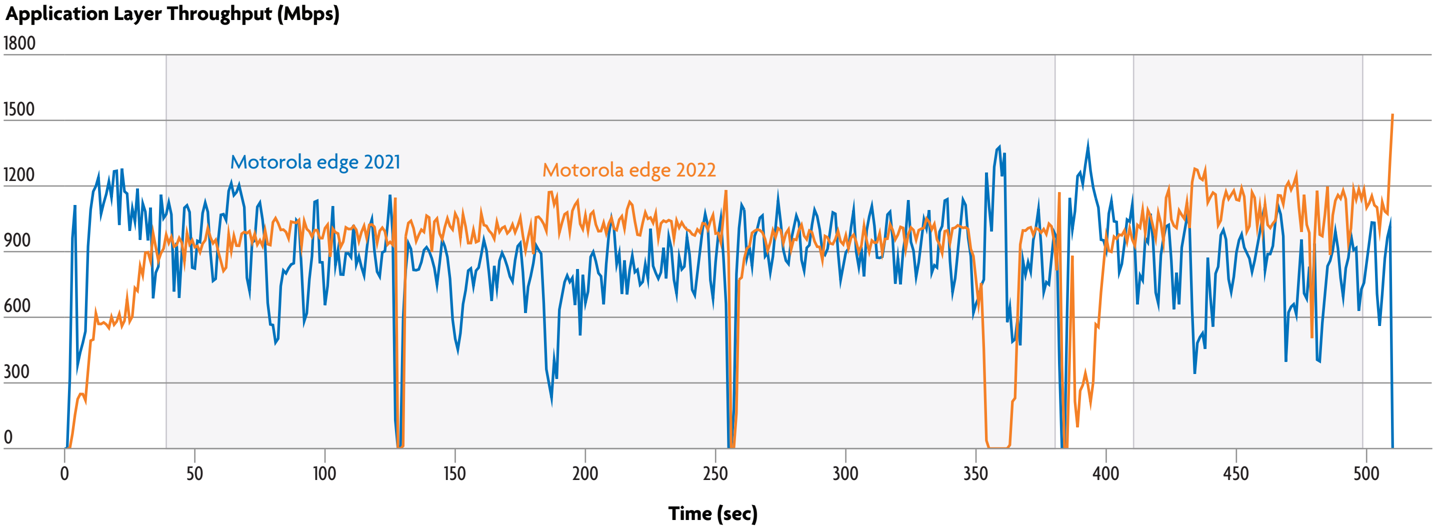


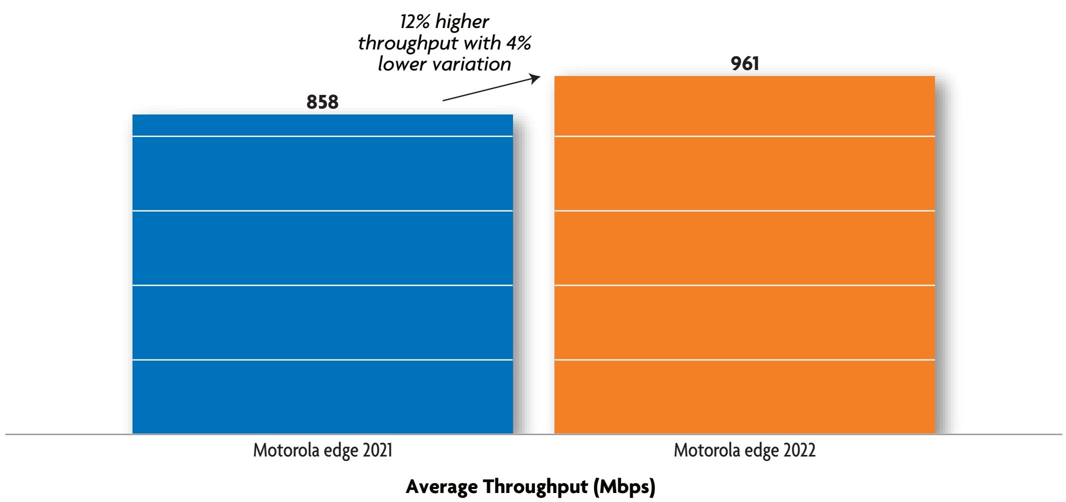
Source: Signals Research Group

4.3 Motorola edge 2022 and Motorola edge 2021

Figure 33 shows the application layer throughput for the two Motorola smartphones during this test. We can't explain why the throughput for the edge 2022 dropped to 0 Mbps just after 350 seconds and there was a slow start to the throughput shortly thereafter when the Umetrix data session resumed. Since the drop in throughput at 350 seconds could have been phone-related, we are including it in the results, but consistent with our methodology, we excluded the period associated with the slow start. The Motorola edge 2022 had 12% higher throughput than the Motorola edge 2021 smartphone, with 4% lower variation in the throughput.

Figure 33. Motorola edge 2022 and Motorola edge 2021 Application Layer Throughput



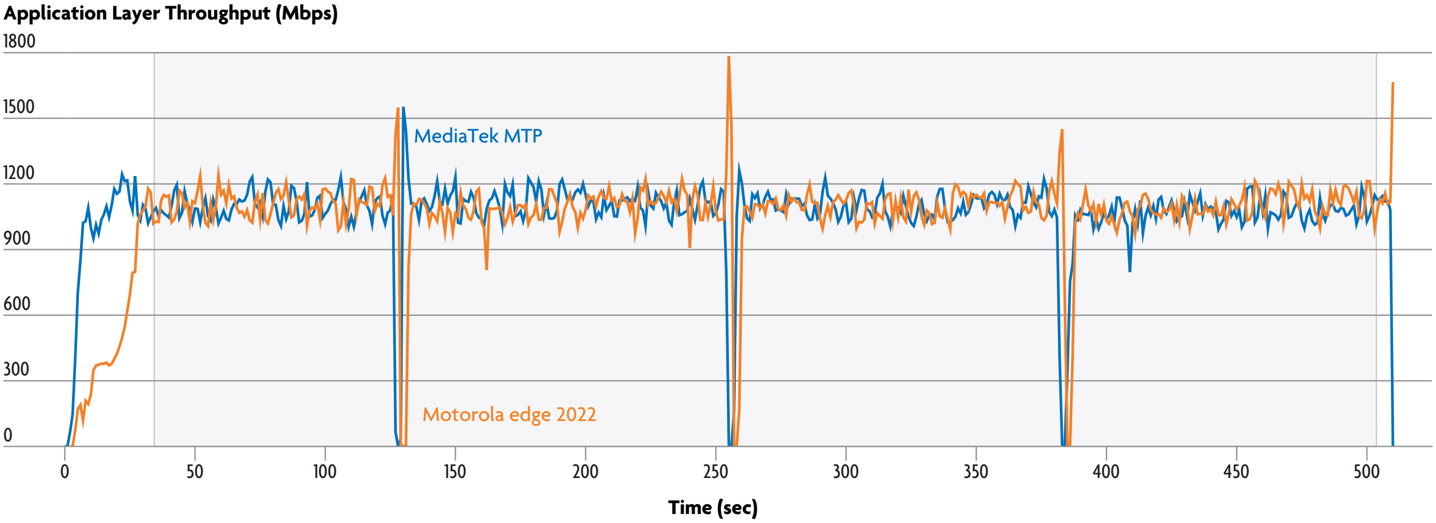


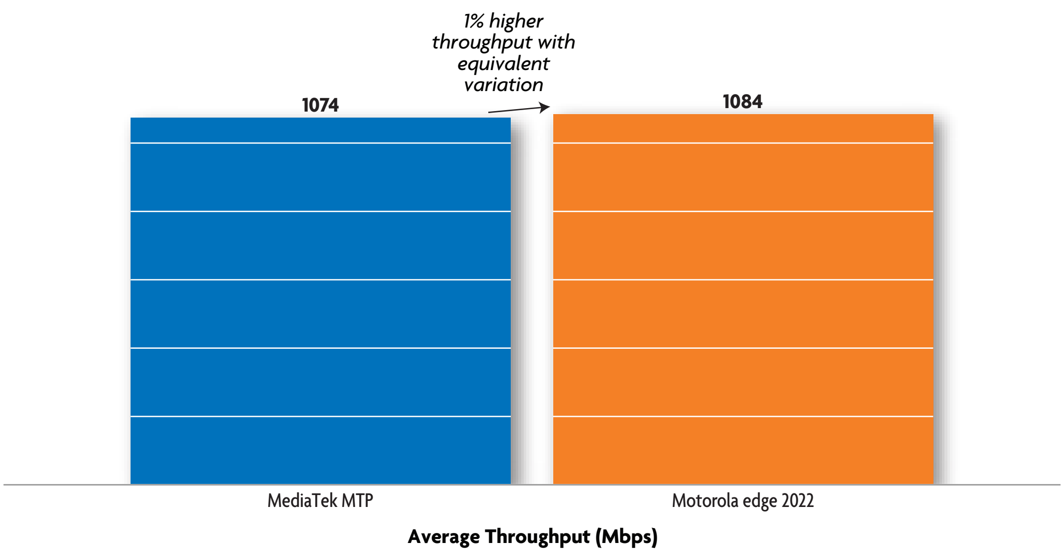
Source: Signals Research Group

4.4 Motorola edge 2022 and MediaTek Mobile Test Platform

As shown in Figure 34, the Motorola edge 2022 and the MediaTek MTP achieved nearly identical throughput with a comparable variation in the throughput. The combined average throughput for the two smartphones exceeded 2.1 Gbps.

Figure 34. Motorola edge 2022 and MediaTek MTP Application Layer Throughput





Source: Signals Research Group

5.0 Location 2 Near/Non Line-of-Site Test Results

The results in this chapter stem from testing at the same location as used in Chapter 4. However, we placed the rotating platter with the two smartphones on the bed of the truck, creating a near/non-LOS view of the serving cell. As shown in Figure 35, from the perspective of a person standing next to the test vehicle there was a LOS view of the adjacent serving 5G radio, but from the perspective of the phones under test, it is evident the directional path between the phones and the 5G radio were blocked by a combination of the bed cover and the sidewalls of the truck. We also note this was a heavily traveled road so larger vehicles could also interfere with the mmWave signals.

Figure 35. Test Location

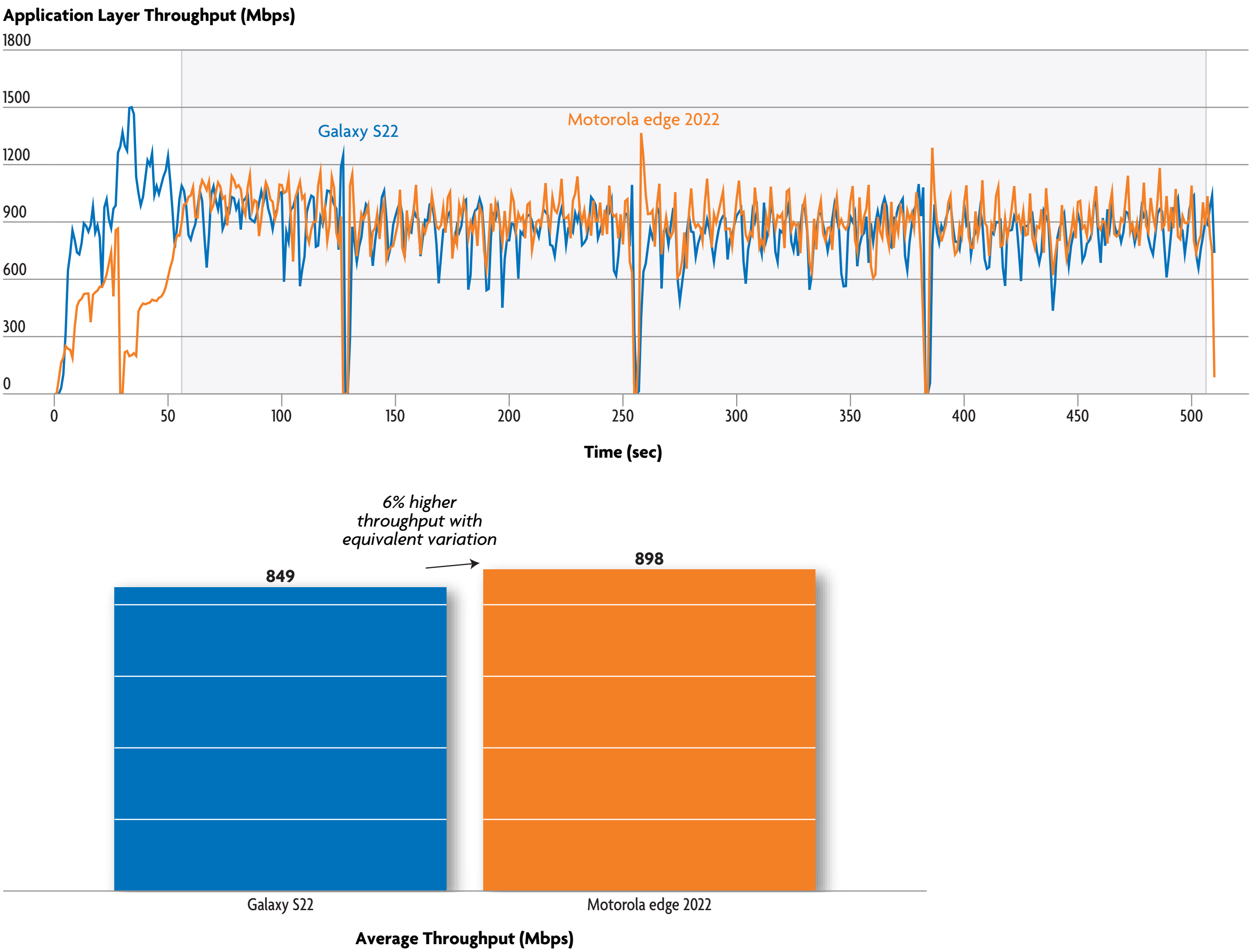
Source: Signals Research Group

5.1 Motorola edge 2022 and Galaxy S22

The Motorola edge 2022 and Samsung Galaxy S22 smartphones had comparable performance at this location, albeit slightly favoring the Motorola smartphone.

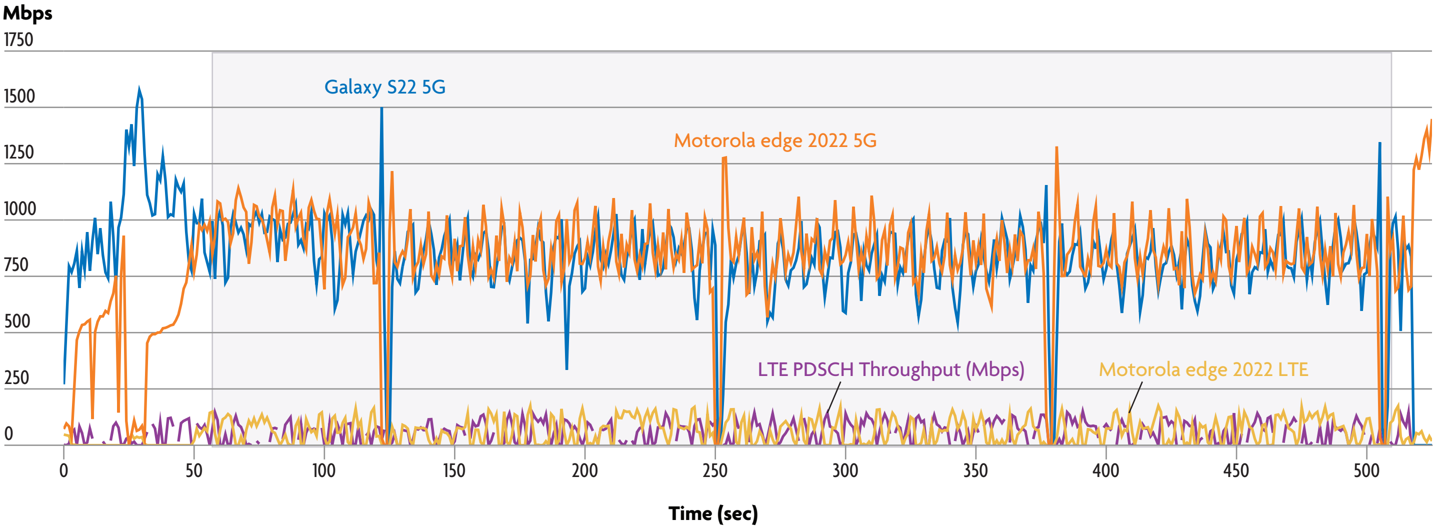
The RF conditions were more challenging with the rotating platter resting on the bed of the truck, so the total throughput was also lower. As shown in Figure 36, the Motorola edge 2022 had slightly higher application throughput than the Galaxy S22 smartphone (6% difference) with equivalent variation in the throughput. At the physical layer (Figure 37), the difference in 5G throughput was only 3%, once again with a comparable variation in the throughput.

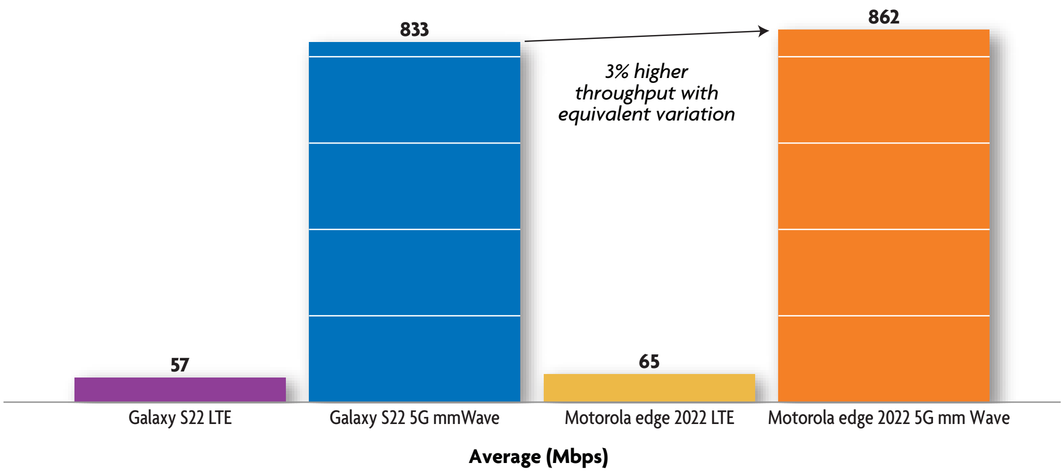
Figure 36. Motorola edge 2022 and Galaxy S22 Application Layer Throughput



Source: Signals Research Group

Figure 37. Motorola edge 2022 and Galaxy S22 Physical Layer Throughput

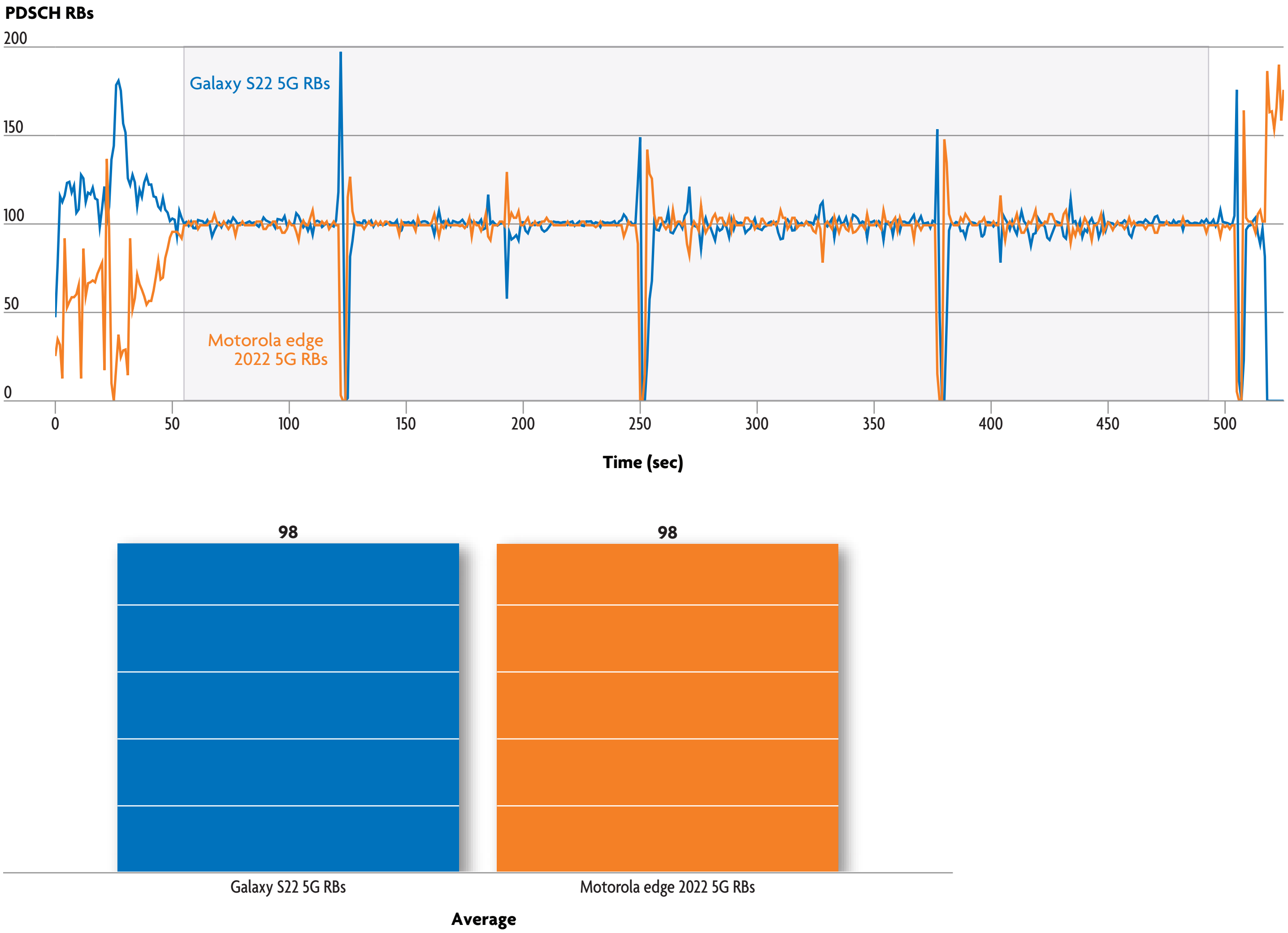




Source: Signals Research Group

Both smartphones used an equal number of network resources, as evident by the information shown in Figure 38.

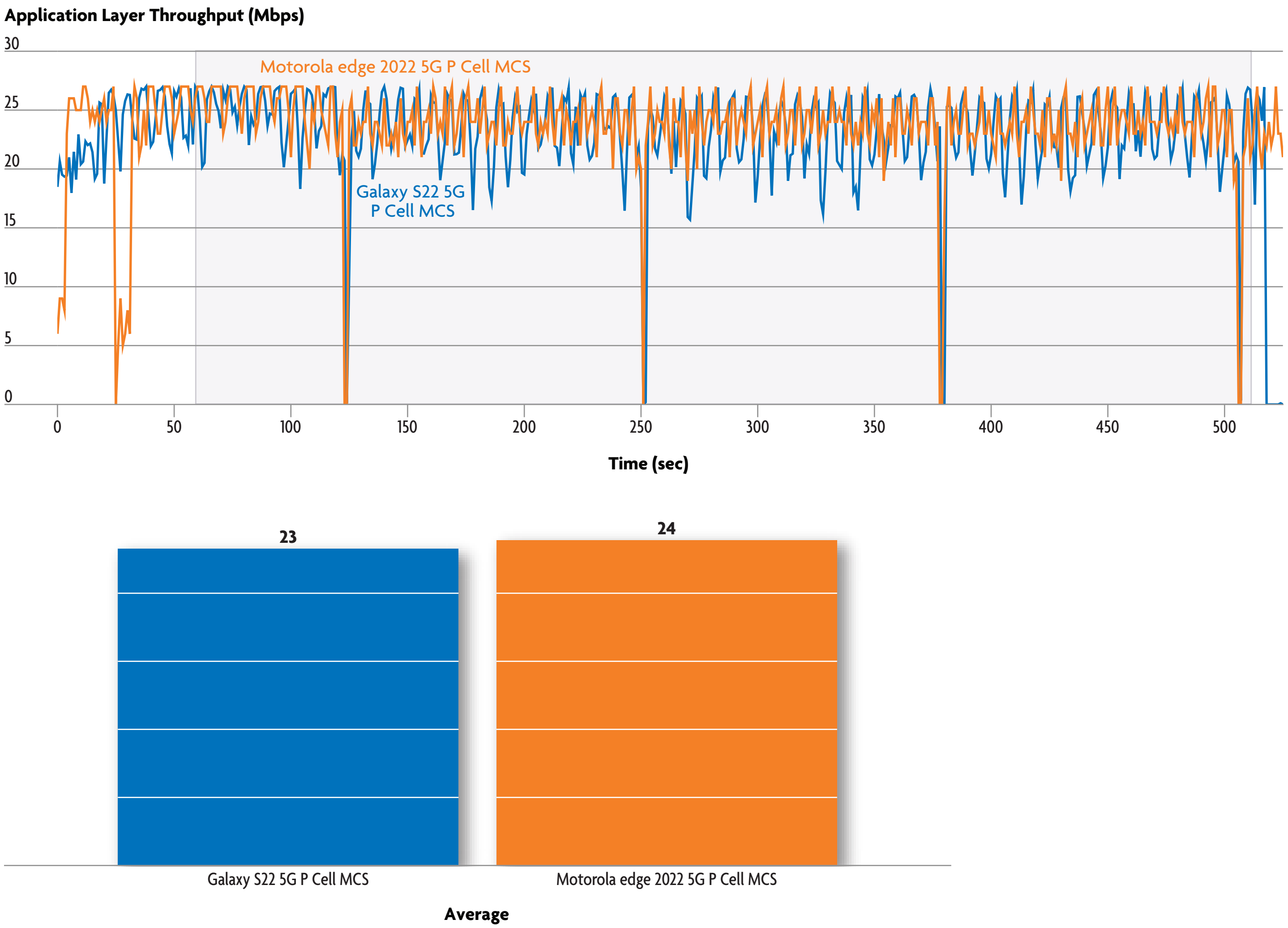
Figure 38. Motorola edge 2022 and Samsung Galaxy S22 PDSCH Resource Block Allocations



Source: Signals Research Group

The MCS allocations slightly favored the Motorola edge 2022 and the variation in the MCS was also 16% lower for the Motorola smartphone, compared with the Galaxy S22.

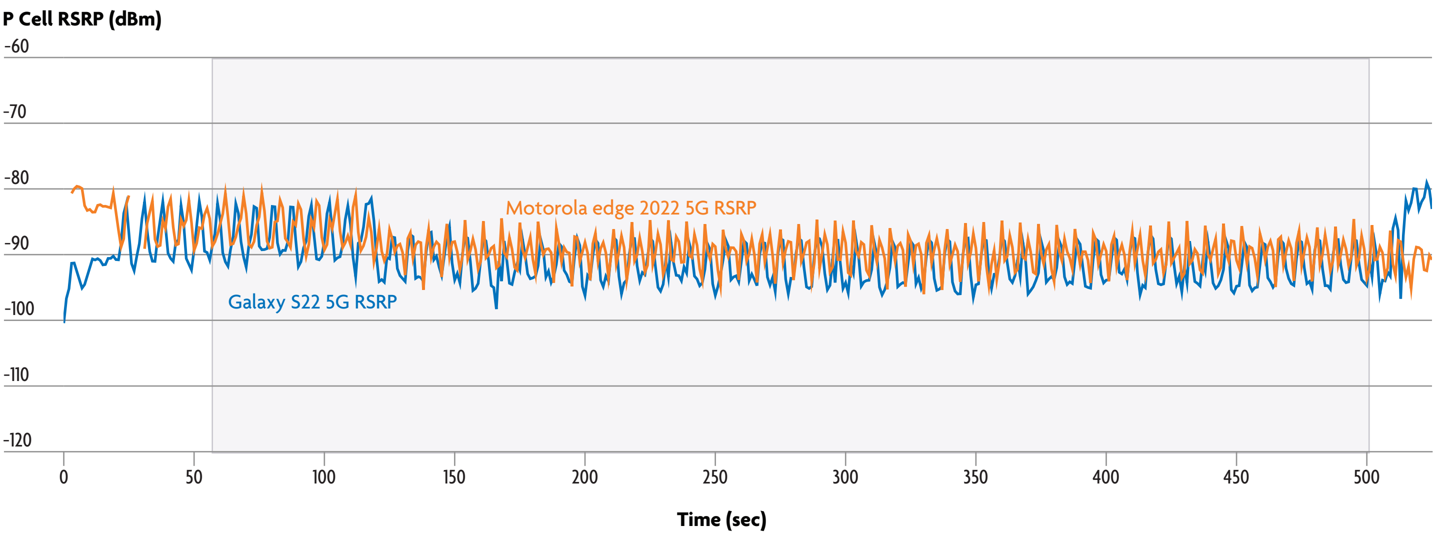
Figure 39. Motorola edge 2022 and Samsung Galaxy S22 Primary Cell MCS Allocations



Source: Signals Research Group

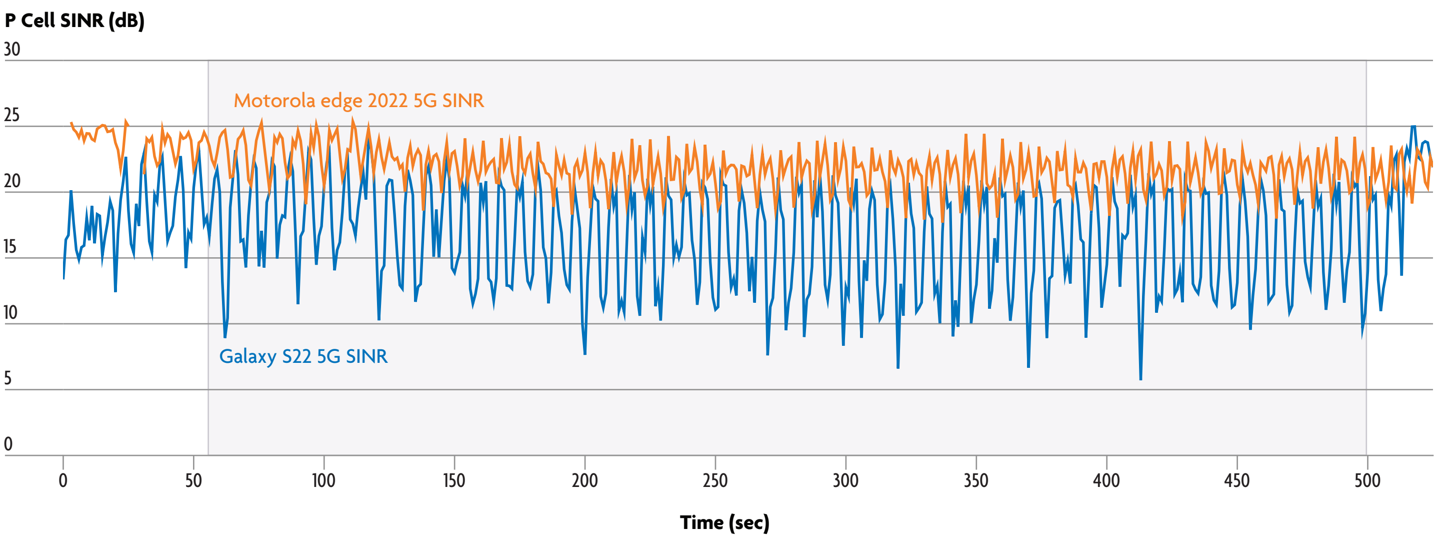
The variations in the RSRP were very similar (Figure 40) with greater variations in the SINR (Figure 41). At the beginning of this test, we adjusted the Galaxy S22 on the platter, which explains the lower RSRP/SINR values at the start of the test and why we excluded them in the analysis. With both RSRP and to a lesser extent SINR, there was a noticeable drop in the values for both smartphones at 125 seconds into the test. This drop coincided with a slight adjustment to the position of the platter, which made the RF conditions slightly more challenging for both smartphones. In this test, it is evident the larger variations in the S22 SINR did not translate into large differences in its throughput. This situation is consistent with our view that the variations in the RSRP and SINR are interesting, and indicative that the smartphones were encountering changing RF conditions, but not directly related to differences in the throughput and its variation.

Figure 40. Motorola edge 2022 and Samsung Galaxy S22 Primary Cell RSRP Measurements



Source: Signals Research Group

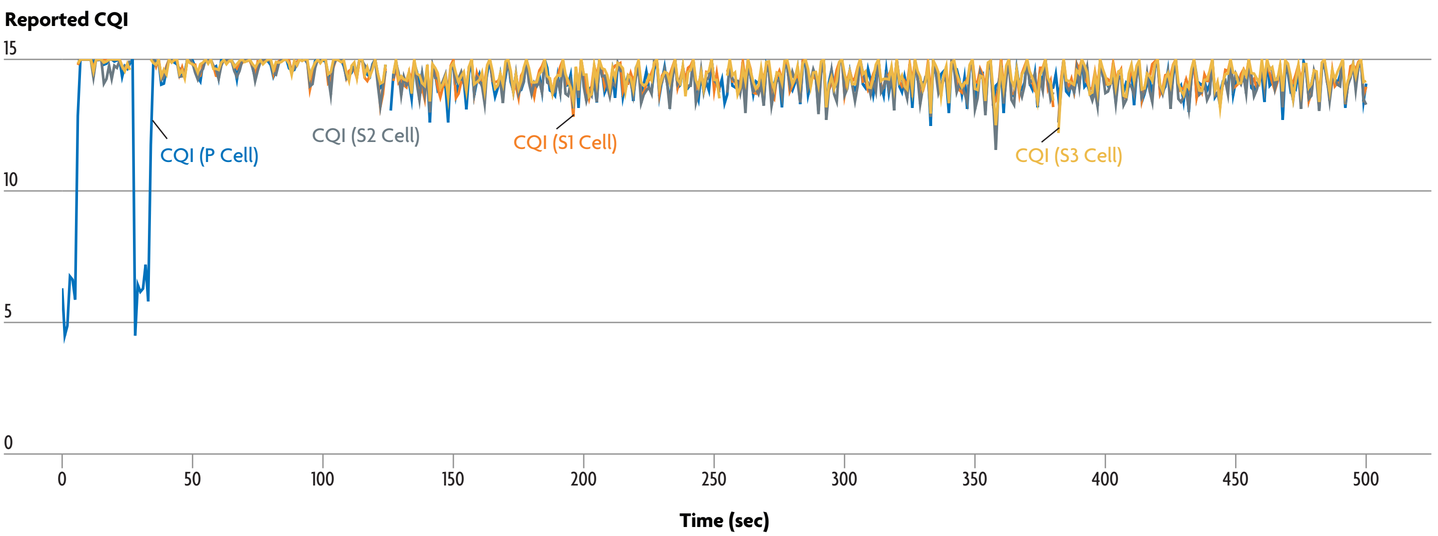
Figure 41. Motorola edge 2022 and Samsung Galaxy S22 Primary Cell SINR Measurements



Source: Signals Research Group

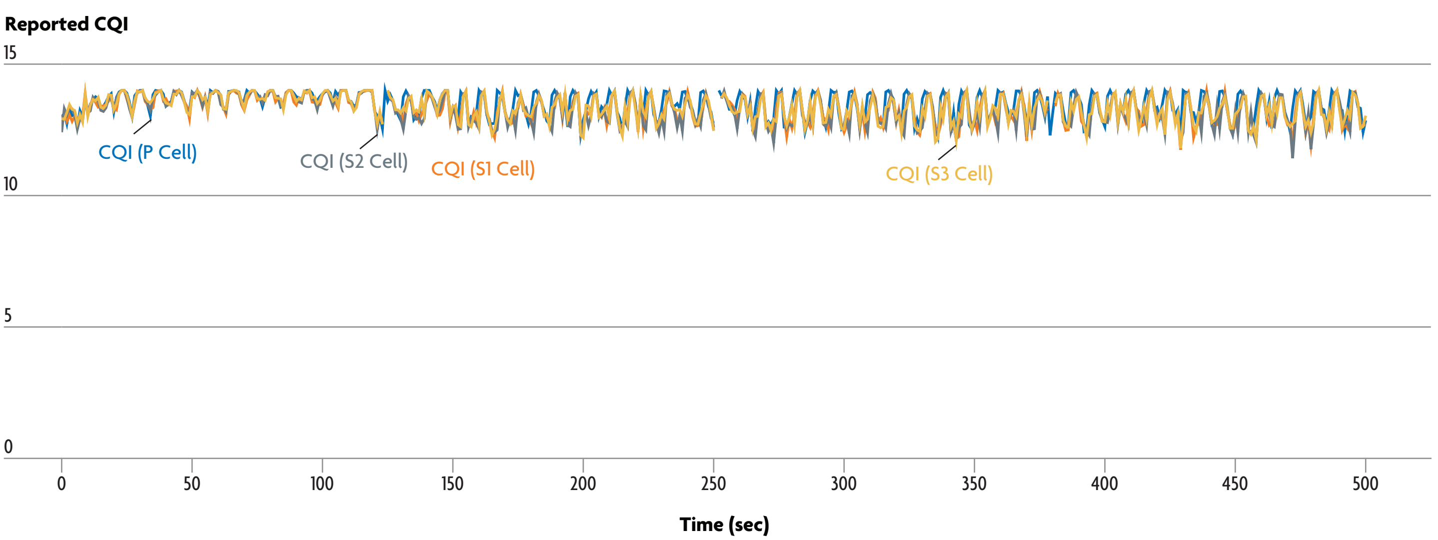
With the more challenging RF conditions, compared with the previous chapter, the CQI was a bit lower with higher variation in the results. Specifically, the variation increased from under 1% in the earlier test to between 3% and 4% in this test. The outcome slightly favored the Motorola edge 2022 smartphone.

Figure 42. Motorola edge 2022 Primary and Secondary Cells CQI Reports



Source: Signals Research Group

Figure 43. Samsung Galaxy S22 Primary and Secondary Cells CQI Reports

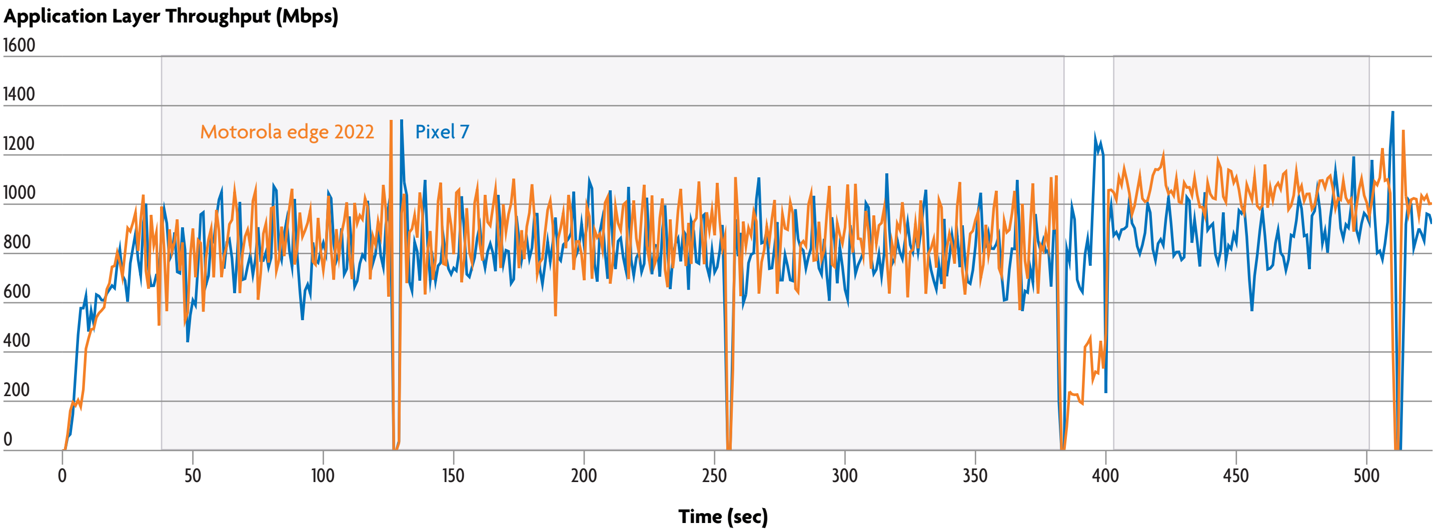


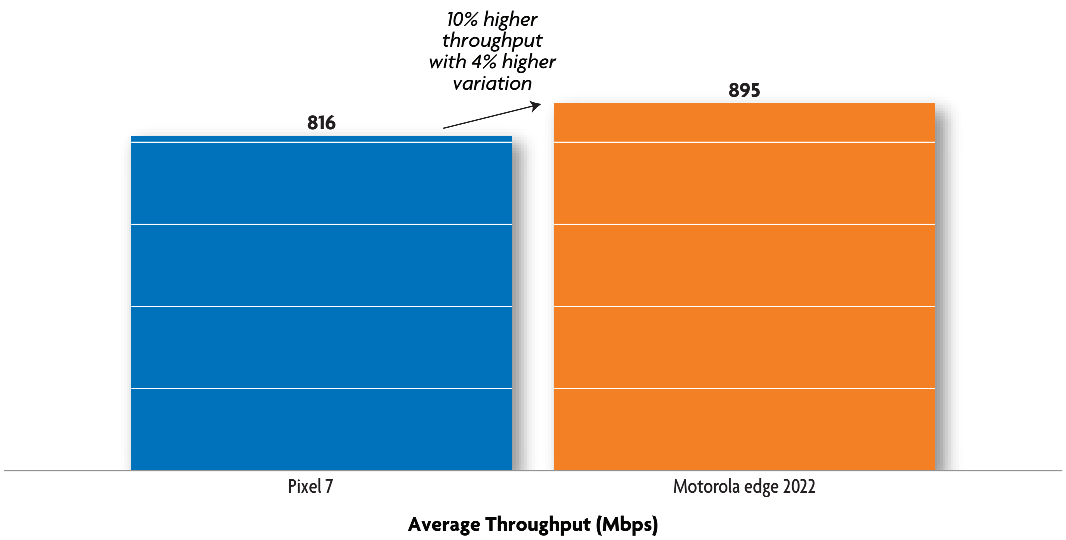
Source: Signals Research Group

5.2 Motorola edge 2022 and Google Pixel 7

In this test the Motorola edge 2022 smartphone achieved 10% higher application layer throughput than the Google Pixel 7. However, the Motorola smartphone also had 4% higher variation in its throughput. Both smartphones had a slow start at the beginning of the test and at the beginning of the last Umetrix data session, so we excluded these periods when doing the analysis.

Figure 44. Motorola edge 2022 and Google Pixel 7 Application Layer Throughput





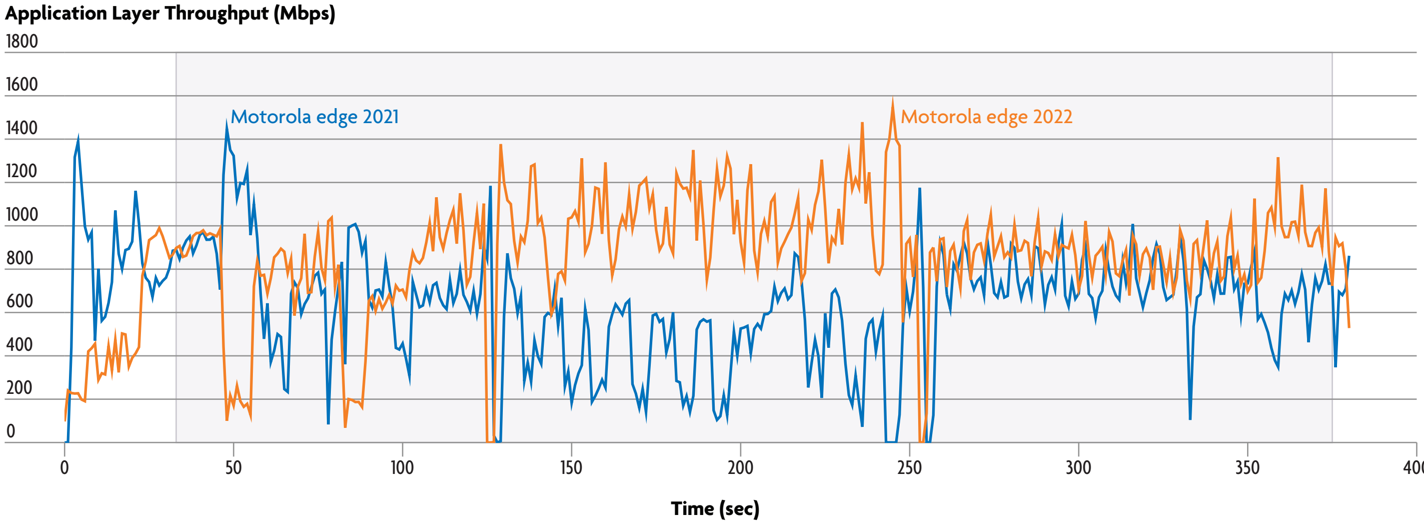
Source: Signals Research Group

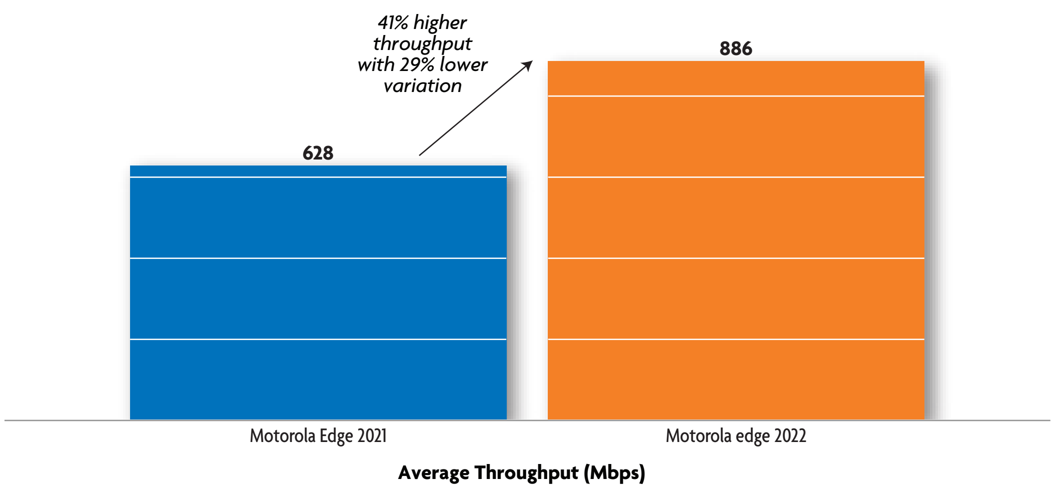
5.3 Motorola edge 2022 and Motorola edge 2021

Both Motorola smartphones had a slow TCP start at the beginning of the test. For the first Umetrix data session both smartphones had widely varying throughput with both smartphones exhibiting better performance at various points during the period. During the second data session, the variation in the throughput was still pretty significant but the Motorola edge 2022 smartphone had consistently higher throughput. Finally, during the third data session, the throughput for both smartphones was more consistent.

We included all highlighted periods in our analysis because the throughput did not appear to be artificially capped – note, for example, the peak in the edge 2021 throughput at ~215 seconds. In other tests, it was very evident in the behavior of the throughput that there wasn't an RF phenomenon taking place. Based on the highlighted region in Figure 45, the Motorola edge 2022 smartphone achieved 41% higher throughput with 29% lower variation in the throughput. If we excluded this region and only included the period from 252 seconds to the end of the test then the edge 2022 smartphone outperformed the edge 2021 smartphone by 21%.

Figure 45. Motorola edge 2022 and Motorola edge 2021 Application Layer Throughput



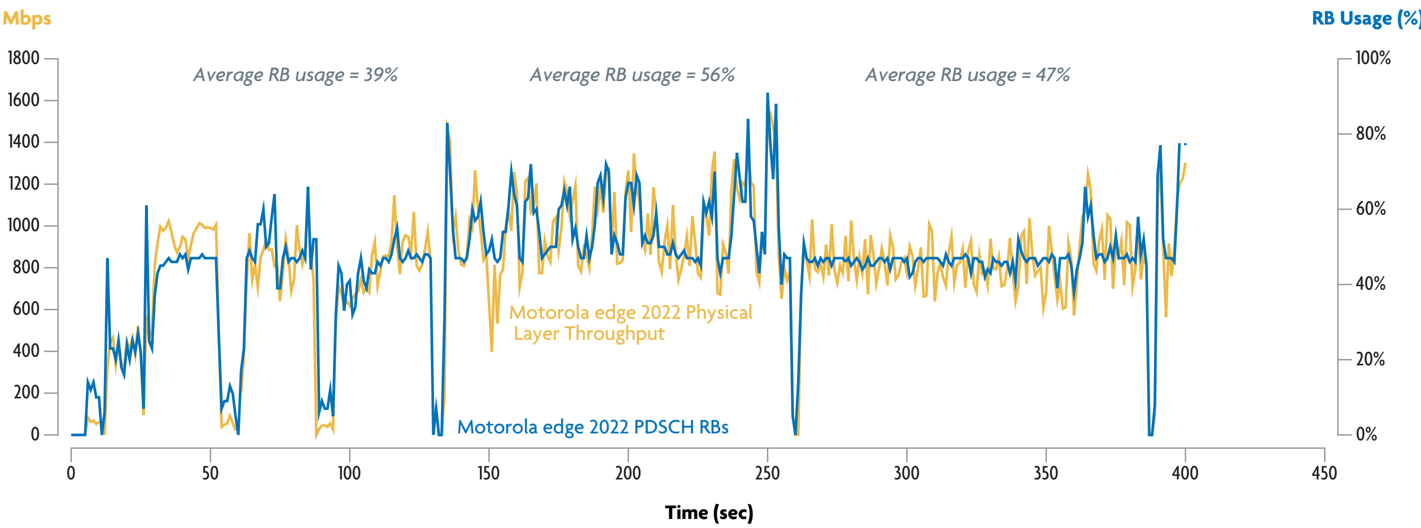


Source: Signals Research Group

In Figure 46 we've plotted the physical layer throughput and the total RB usage as a percentage of total available RBs for the Motorola edge 2022. The information in this figure helps justify our decision to include the full range of results. We make this statement because the RB usage for the Motorola edge 2022 smartphone does not suggest a bias in the network scheduler behavior. The RB usage was 56% during the second data transfer session, but the slightly higher than 50% RB usage does not explain the large difference in throughput between the two smartphones. During the first data transfer session the Motorola edge 2022 smartphone only used 39% of the possible resource blocks. We point out we did this test right outside of Orchestra Hall and we noticed multiple members of the Minnesota Orchestra inside the lobby for a photo shoot. It wouldn't be unreasonable to conclude some of the musicians were Verizon subscribers and using their smartphones at the time we did this test.

Resource block allocations for the Motorola edge 2022 smartphone suggest there wasn't any bias in the network scheduler behavior.

Figure 46. Motorola edge 2022 Physical Layer Throughput and Total RB Usage



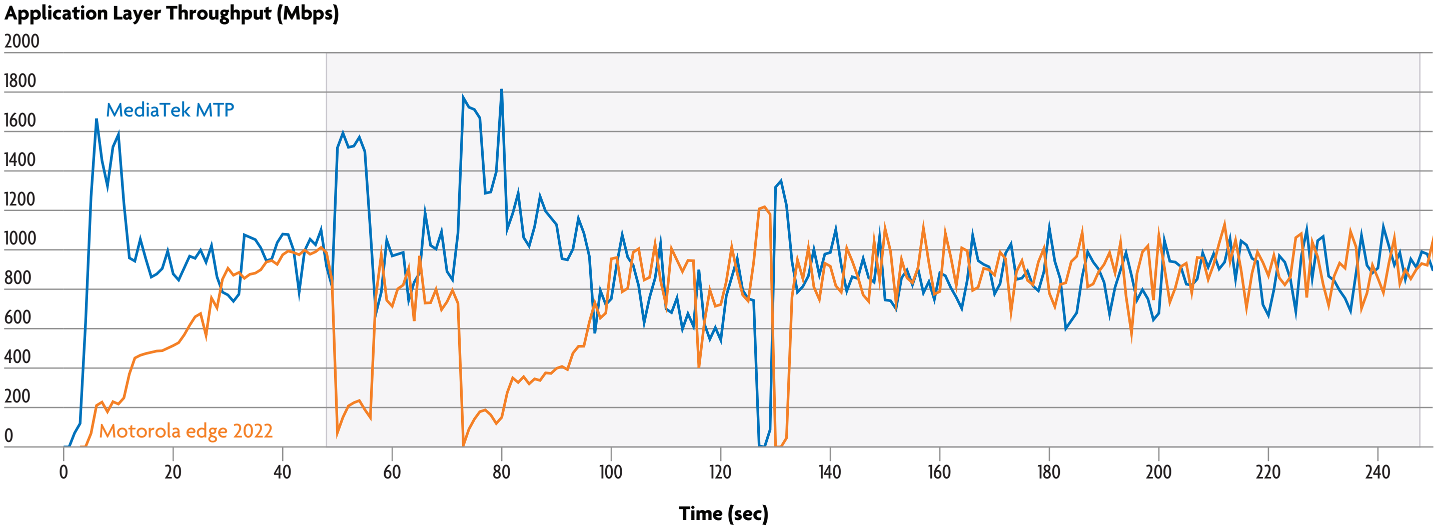
Source: Signals Research Group

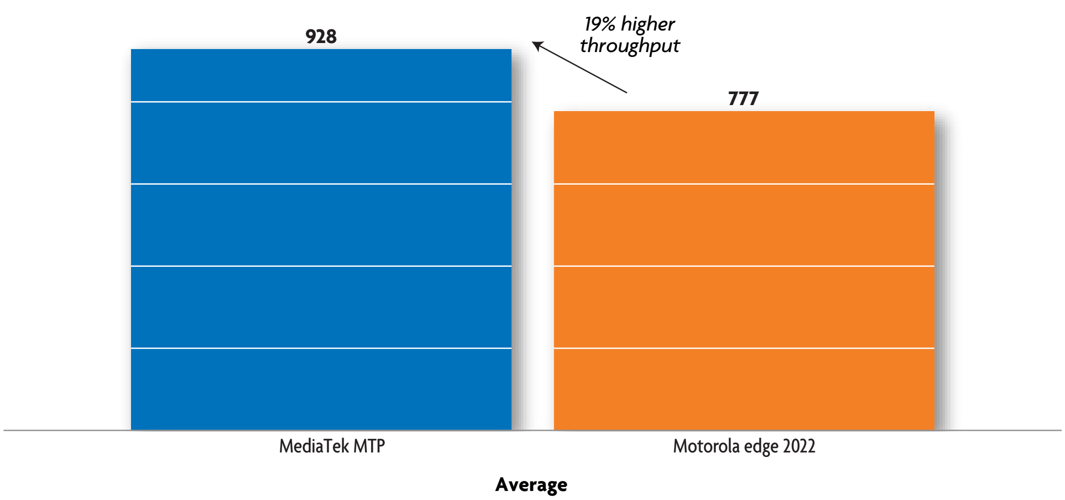
5.4 Motorola edge 2022 and MediaTek Mobile Test Platform

We excluded the initial slow ramp of the Motorola edge 2022 smartphone at the start of the test, but once it achieved an equilibrium in its throughput, we included all remaining results. Like the results in the previous section, lower throughput exhibited by the Motorola edge 2022 smartphone benefited the MediaTek MTP. As evident in Figure 47, the MediaTek MTP achieved 19% higher throughput than the Motorola edge 2022 smartphone.

The MediaTek MTP achieved 19% higher throughput than the Motorola edge 2022 smartphone.

Figure 47. Motorola edge 2022 and MediaTek MTP Application Layer Throughput





Source: Signals Research Group

6.0 Location 3 Results

We tested all the previous pairings of smartphones at this location, positioned just under 100 meters from the serving cell site. We tried moving further away to an adjacent parking lot with near-LOS conditions. Although phones could attach to 5G mmWave and obtain ~1 Gbps throughput, some phones would also fall back unexpectedly to Band n77, even while not rotating on the platter. Since we wanted repeatability in the tests, we remained at the closer location, shown in Figure 48. We also discovered while testing at this location that the battery level in the Motorola edge 2022 smartphone had dropped below 10%, resulting in the phone entering a power saving mode which could have impacted its performance in unknown ways. Unlike the other smartphones, we used the edge 2022 smartphone in all the tests, so it was impacted by frequent use and the much larger amount of data that we transferred with the phone. We noticed this situation after testing with the Galaxy S22 and Pixel 7 smartphones, but we didn't realize the severity of the situation until we started analyzing the data.

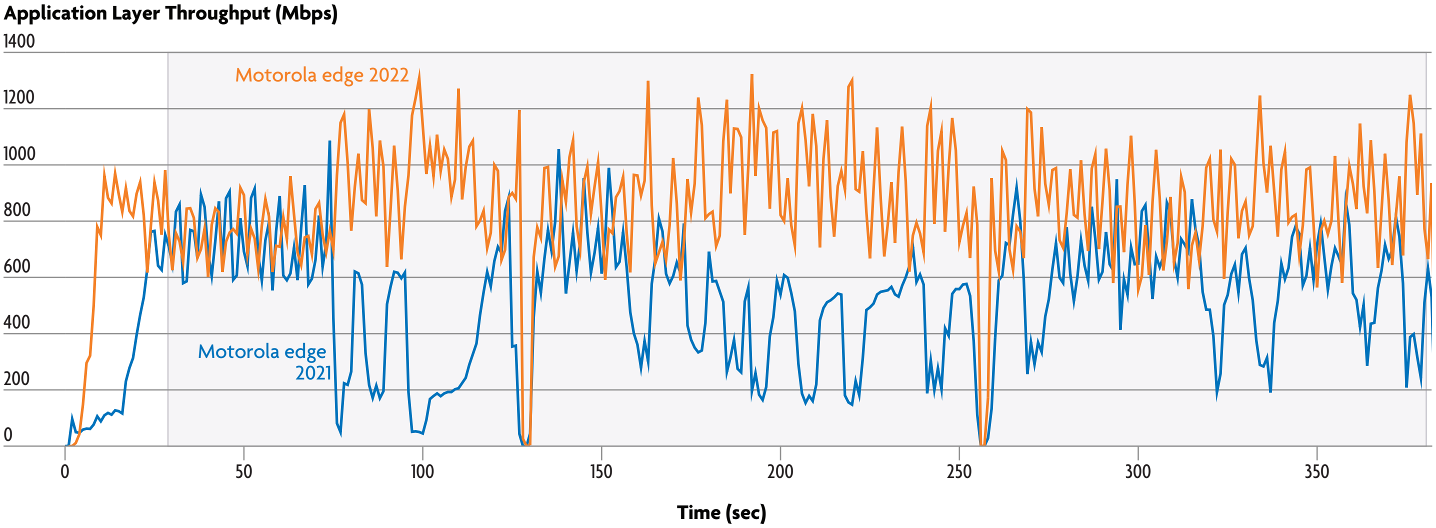
Figure 48. Test Location

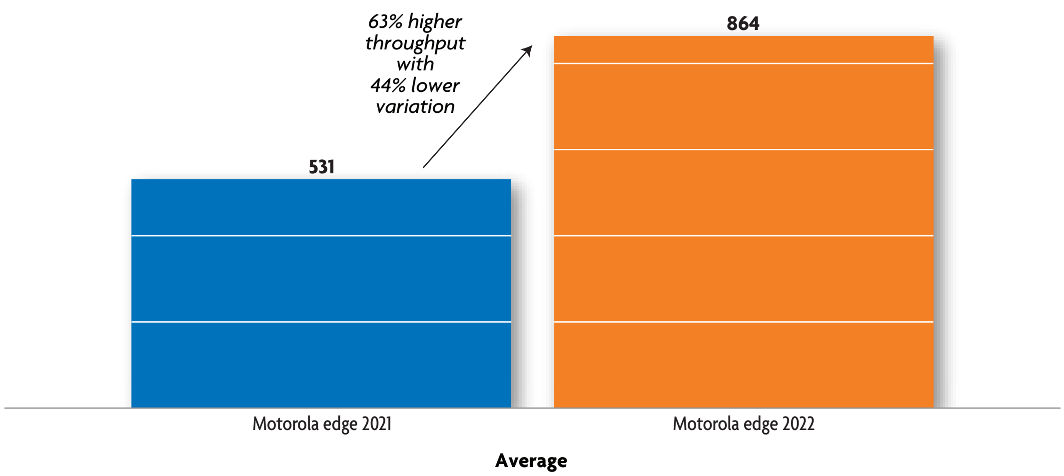
Source: Signals Research Group

Since we had another Motorola edge 2022 smartphone in our possession, we used this phone when testing with the Motorola edge 2021 smartphone and the MediaTek MTP. We are including those results in this chapter.

Based on application layer throughput, the Motorola edge 2022 smartphone outperformed the Motorola edge 2021 smartphone by 63% with 44% lower variation in the throughput. Figure 49 provides this information.

Figure 49. Motorola edge 2022 and Motorola edge 2021 Application Layer Throughput

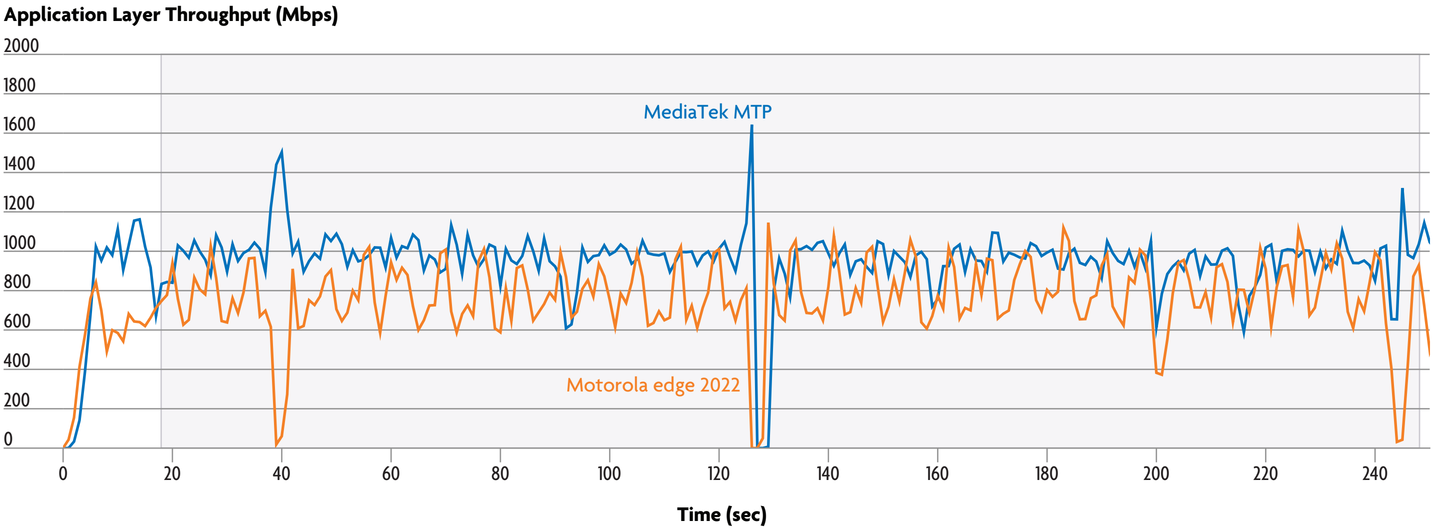


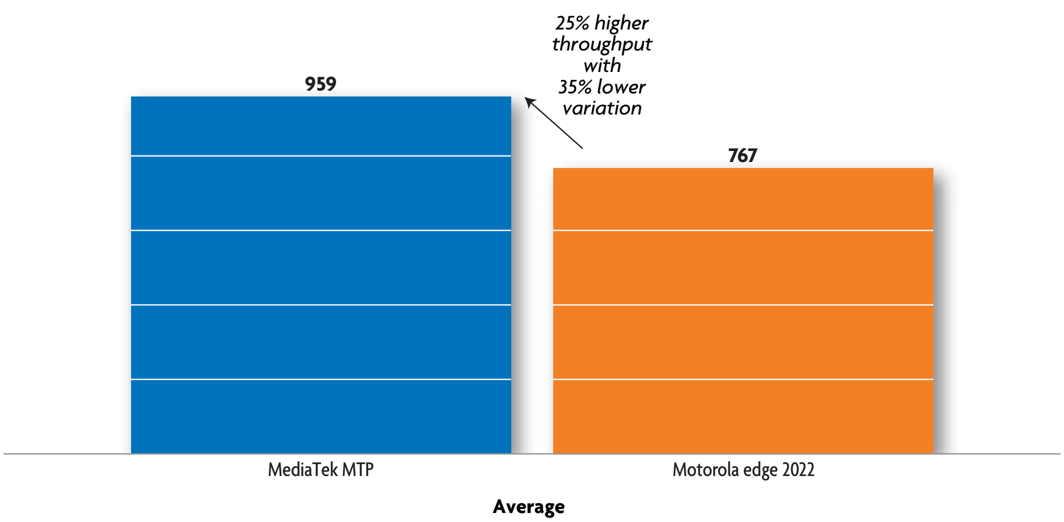


Source: Signals Research Group

Finally, in comparative testing between the two MediaTek-enabled devices, the MTP outperformed the Motorola edge 2022 smartphone by 25%, with 35% lower variation in the throughput.

Figure 50. Motorola edge 2022 and MediaTek MTP Application Layer Throughput





Source: Signals Research Group

7.0 Test Methodology

We conducted this benchmark study in downtown Minneapolis, MN, in early January. The network in Minneapolis was limited to four mmWave carriers (400 MHz) so that bandwidth defined the upper limit of the throughput. We know the Galaxy S22 smartphone supported 8x100 MHz of spectrum and we believe all other smartphones were limited to 4x100 MHz. Testing in a market with 800 MHz of spectrum would have resulted in the S22 achieving much higher throughput but it would not have negated the other performance attributes we observed and which were the primary focus of this study.

We selected three test locations where there was 5G mmWave coverage and where we could safely park for an extended period – not an easy task with all the piles of snow in the area and along the streets. At each test location, we used a rotating platter with two phone holders to test two smartphones in parallel. In each comparative test we used the Motorola edge 2022 smartphone as the reference smartphone. We placed the platter on the truck bed cover of our test vehicle at all locations. At one location, we placed the platter on the bed of the truck with the bed cover above the platter. The combination of the sidewalls of the truck and the bed cover completely blocked the smartphones' view of the serving 5G mmWave radio. Earlier pictures in this report showed the test setup.

We had hoped to test in additional locations, or at least locations with more challenging RF conditions, but we quickly discovered that there was a very conservative handover threshold between 5G mmWave and Band n77 whereby the phones would drop to the mid-band 5G frequency (Band n77), even if the 5G mmWave signal was quite good. We didn't have the ability to lock the phones to 5G mmWave so we had to restrict our testing to locations where we felt the phones would remain on 5G mmWave. It is our belief that with poorer 5G mmWave radio conditions, the difference in performance between the Motorola edge 2022 benchmark phone and the commercial smartphones would have been greater than shown in this report.

Once we started the downlink data transfers and activated the chipset logging on the phone (when possible), we placed the smartphones onto the phone holders so that the two phones faced each other. We then turned on the platter so that it continuously rotated for the duration of the test – nominally around 8 minutes, although in a few cases the length of the test was cut short. Although we don't include the results in this report, we did repeat a few tests to confirm consistency in the data.

The rotating platter with the phone holders served a few purposes. First, the rotating platter ensured both smartphones were exposed to the same RF conditions. Second, the rotating platter ensured consistency of the network conditions encountered by the two phones within the test. The conditions could change, but the phones would be equally exposed to them. Lastly, and most importantly, the rotating platter allowed us to focus the 5G mmWave performance of each smartphone/chipset modem on its beam tracking capabilities. Consumers may not spin around and around, but they do twist, turn, and walk while using their phones, not to mention move the phone around while standing still, and our approach seemed like the best means of focusing on mmWave performance with a non-stationary smartphone.

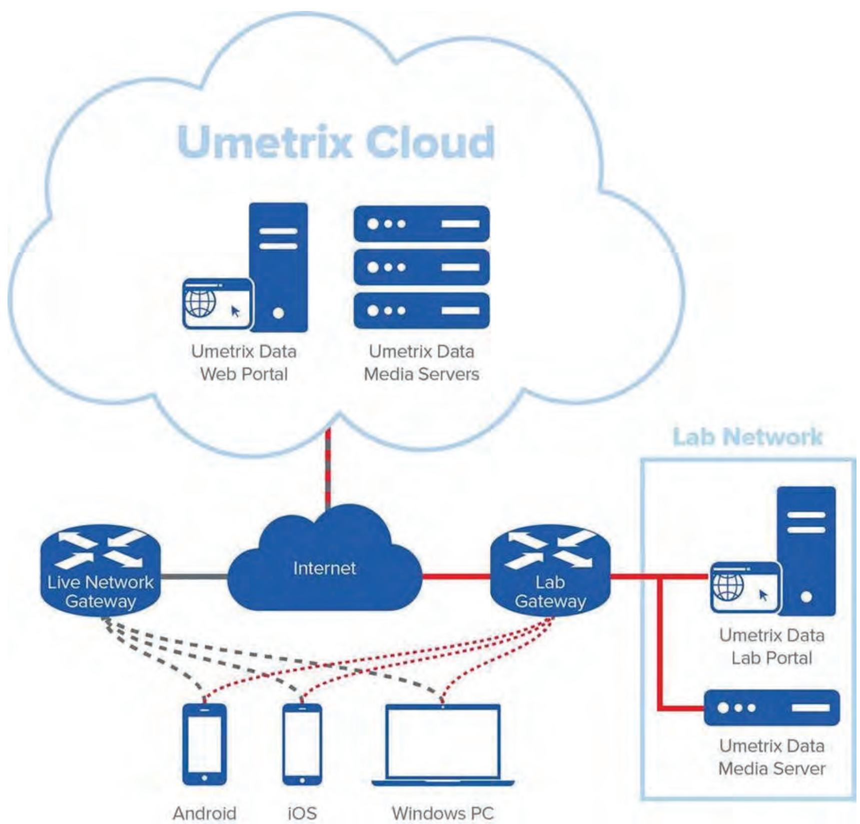
Our testing methodology seemed like the best means of focusing on mmWave performance with a non-stationary smartphone.

We used Umetrix Data from Spirent Communications to generate the full buffer HTTP data transfers that we used to load the network. The Linux servers, which hosted the Umetrix data platform, used the CUBIC congestion control algorithm. Although the servers we used were located in California, they were more than sufficient to generate far more data traffic than the 5G mmWave network could support. Occasionally, the smartphones experienced what resembled to be a slow TCP ramp when starting their data sessions. It didn't happen all the time – something we would expect of a slow TCP was the root cause – but it did happen with all smartphones at some point during our testing. Since we felt the slow ramp was due to window sizing issues, either within the phones, the network,

We used Umetrix Data from Spirent Communications to generate the full buffer HTTP data transfers that we used to load the network.

or a combination of the two, and not specific to RF performance, we excluded those periods in our analysis when one or both smartphones experienced it. Looking at the data, we believe that generally the second phone to start its data transfer session was more likely to encounter the TCP slow start. Figure 51 illustrates the Umetrix Data architecture.

Figure 51. Umetrix Data Architecture



Source: Spirent Communications

For this benchmark study, we used a combination of physical layer results, as reported by the chipset modem, and application layer throughput, to analyze the data. For the Galaxy S22 smartphone, we used XCAL-Solo from Accuver Americas to log the chipset data coming from the 5G modem. Since the XCAL-Solo unit is a handheld unit, we could easily place the unit on the rotating platter along with an external battery pack. For the Motorola edge 2022 smartphone, we used its internal logging capabilities to capture its performance. Accuver's drive test tools support all chipsets, but they require access to the chipset diagnostic port, which isn't always available. It wasn't visible with the Google Pixel 7 and Motorola edge 2021 smartphones. Figure 52 shows a picture of the XCAL-Solo unit.

We used XCAL-Solo from Accuver Americas to log the chipset data coming from the 5G modem.

Figure 52. XCAL-Solo

Source: Accuver Americas

For those phones where we did not have chipset logging capabilities, we relied on the Umetrix Data platform to obtain the application layer throughput. This information is stored on the Umetrix server along with other useful information, including time stamps, GPS coordinates, and useful RF parameters, including serving cell PCI, primary cell frequency and 5G band, not to mention RSRP and SINR, as reported by the Android OS. We can, and did, provide richer analysis with the physical layer information, but the results based on application layer throughput are equally valid.

We could also leverage physical layer information captured by the Motorola edge 2022 smartphone to gain insight to the physical layer performance of the other smartphones. For example, we confirmed with both the Galaxy S22 and the Motorola Edge 2022 that 5G mmWave accounted for the vast majority of the total throughput. Based on this information, we could infer that other smartphones behaved in a similar manner and that the performance differences we observed were directly attributed to 5G mmWave performance. Secondly, we could gain some insight into the network scheduler behavior for the smartphones, based on observing how the network was scheduling the Motorola edge 2022 smartphone.

We leveraged physical layer information captured by the Motorola edge 2022 smartphone to gain insight to the physical layer performance of the other smartphones.

We analyzed the following physical layer parameters: physical layer throughput (LTE and 5G), RB utilization (4 mmWave carriers), MCS allocations (P Cell), SINR and RSRP (P Cell), CQI (4 mmWave carriers). To some extent, physical layer throughput is the most important metric. However, the other parameters provide insight into how the throughput was obtained. For example, we showed in the previous chapter how large variations in the throughput was entirely due to variations in the reported MCS/CQI values and not to the RB allocations. This insight allows us to confirm the performance differences we observed in the data were due to the beam tracking capabilities of the smartphones/chipsets and not to the network scheduler.

In addition to providing average results from several metrics, we also provided the variance of these values. By our definition, variance is the average value of the metric divided by its standard deviation. This approach was necessary to account for differences in the throughput. A much larger average throughput could likely have a higher standard deviation in the values, but still deliver more consistent results.

8.0 Final Thoughts

This 5G mmWave benchmark study compared the performance of four commercial smartphones and a mobile test platform, representing 5G chipset modems from three suppliers. We offer a few final thoughts to summarize our analysis of the results and experience while testing with the five devices.

- The beam tracking capabilities of a 5G chipset play a critical role in determining the performance of a 5G mmWave smartphone. Although it is somewhat straightforward to have good beam tracking while the smartphone is stationary, it becomes more difficult when the smartphone is moving through the network or while a consumer is standing or sitting still while turning or repositioning the phone across his or her body.
- There are meaningful differences in the beam tracking capabilities of today's 5G chipsets. With relatively ideal conditions, these distinctions do not translate into noticeable performance differences. However, with more challenging RF conditions, we documented meaningful double-digit percentage differences in average throughput as well as large variations in the instantaneous throughput. With our analysis of physical layer parameters, we could directly trace these differences to the constant changes in the RF environment and the ability of the chipsets to select the best receive path for the transmitted 5G mmWave signal coming from the serving 5G gNB. It is also worth noting that the higher price of the smartphones we tested does not always correlate to having better RF performance.
- From the tests we conducted, the Motorola edge 2022 smartphone and the MediaTek MTP, both with the MediaTek 5G modem, delivered the best results – higher average throughput with lower instantaneous variation – compared with the other smartphones we tested.
- More investigation into the root causes of what we believe were TCP window sizing issues are warranted with follow-on corrective actions taken to optimize performance, irrespective of the RF conditions.
- Additional testing with more challenging RF conditions would likely result in even greater separation of the results we documented in this report. However, to prove this thesis, 5G mmWave networks will need to have less conservative handover thresholds with the underlying mid-band 5G spectrum. Even if we didn't do these tests, we believe operators should take better advantage of their 5G mmWave network when it is overlaid on a mid-band 5G network. The eventual adoption of NR-DC (5G New Radio – Dual Connectivity) would allow the smartphone to use both networks simultaneously, thereby making the handover thresholds obsolete, while adding an interesting dimension to a benchmark study.