5G mmWAVE IS ALIVE AND WELL IN TOKYO, JAPAN

A THIRD-PARTY BENCHMARK STUDY OF mmWAVE PERFORMANCE IN TOKYO, JAPAN

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Prepared by
Signals Research Group

SiGNALS
Research Group
www.signalsresearch.com

Study Conducted for Qualcomm

As the sole authors of this study, we stand fully behind the results and analysis that we provide in this paper, which leverage a methodology consistent with our benchmark studies that we have conducted for more than a decade.

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)

Key Highlights

Signals Research Group (SRG) conducted a performance benchmark study of 5G mmWave in Tokyo, Japan in late April 2022. This study marks our fourth mmWave benchmark study that we have done on behalf of Qualcomm, not to mention several other 5G mmWave studies that we have done on our own since operators launched the first networks back in 2019. One benefit of doing all these studies is that we've been able to track the evolution of the technology, including new capabilities, and the enhanced performance of existing features. Further, our mmWave testing is no longer relegated to the United States. Last year, we did our first 5G mmWave benchmark study in Europe (Helsinki, Finland) and for this study we ventured off to Tokyo where we had the opportunity to test 5G mmWave on a few different operator networks.

One nicety of all this work is that it is never ending, or at least we don't see it ending anytime soon. The industry is in its early stages of 5G, both from a market adoption perspective as well as with respect to technology advancements. 3GPP Release 15 is out the door, but features associated with Release 16 and beyond are still in their infancy. There will be new use cases forthcoming – industry-related use cases are an example – as well as the introduction of new Release features and pending vendor enhancements to enrich the capabilities of today's networks. For us, the most compelling and near-term opportunities for 5G mmWave include support for up to four carrier aggregation in the uplink direction (4x100 MHz), mmWave Standalone (SA) networks for CPEs targeting fixed wireless access use cases, and the combining of 5G mmWave and mid-band 5G assets with NR-DC (New Radio Dual Connectivity). NR-DC will allow mobile devices to simultaneously leverage the mid-band and 5G mmWave spectrum to provide increased data speeds, improved coverage, and more seamless mobility when moving into and out of 5G mmWave coverage.

Key highlights from our benchmark testing in Tokyo include the following:

➤ Uplink 5G mmWave carrier aggregation (2x100 MHz) had a substantial impact on uplink data speeds, not to mention total uplink capacity. The second 5G mmWave carrier nearly doubled the average uplink data speeds over what was possible with a single carrier. It wasn't uncommon to document 5G mmWave uplink physical layer throughput at or above 300 Mbps with an additional contribution from the LTE anchor cell. 5G mmWave uplink performance had an effective range of approximately 200 meters, at which point average uplink speeds of just under 100 Mbps were observed.

➤ Depending on the test scenario and the specifics of what we compared, we found that the 5G mmWave uplink performance was up to four times higher than when testing the mid-band 5G performance. In other tests, the gain was a "more modest" or two times higher. We note that mid-band 5G uplink throughput (100 MHz TDD) was typically in the range of 50 to 70 Mbps, peaking at nearly 80 Mbps. This outcome suggests the mid-band network was lightly loaded in the uplink direction, at least for now. Combined with the observations in the first bullet it is evident that at distances up to 200 Mbps from the cell site, there is a very good chance the uplink throughput on 5G mmWave will exceed that of mid-band 5G spectrum while at closer distances the performance advantage will be even more significant.

➤ The peak downlink spectral efficiency, or the total throughput delivered for a given amount of spectrum, has increased by 66% since our initial 5G mmWave tests back in April 2019. In our testing in Tokyo, we frequently encountered sustained peak data speeds at or slightly greater than 2 Gbps (even at 160 meters from the serving cell), compared with only 1.2 Gbps when we conducted our first study. In our first study, the effective range of 5G mmWave was not nearly as great as what we observed in Tokyo. Both results were achieved with 400 MHz of mmWave spectrum, meaning that operators with 800 MHz of spectrum should expect up to a 2x increase in total peak throughput.

- Despite the strong performance, we identified opportunities for improvement, many of them not directly related to 5G mmWave. For starters, in some dense areas, we encountered frequent/nearly continuous handovers involving the LTE anchor cell – some of the assigned LTE cells were also not mapped to the adjacent 5G mmWave radio so the network had no way of knowing mmWave capabilities existed. In addition to impacting the LTE throughput these handovers subsequently impacted what we observed over 5G mmWave. This "issue" is easily addressed, and the problem has nothing directly to do with mmWave performance, but it is something that an operator needs to include as part of the network optimization activities.
- The smartphone also returned to the LTE RRC Connected state each time there was an LTE handover. Based on tests in other 5G mmWave networks, we would have expected the smartphone to remain in the NSA Connected state. Lastly, in some tests we documented frequent switching between SSB beam indices and generally much greater than we are accustomed to seeing. Although some of these changes helped boost performance, we felt many of them were unnecessary and in several cases actually had a detrimental effect on results (lower SINR, lower RSRP and lower throughput). Timely handovers from mid-band 5G to 5G mmWave when entering mmWave coverage is another opportunity for improvement. The forthcoming availability of NR-DC functionality could go a long way toward addressing this issue.

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

Index of Figures and Tables

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.

One key focus area of our research where we are widely recognized is 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 24 benchmark studies in Signals Ahead 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.

This paper marks the fourth 5G mmWave study that we have done for Qualcomm. Since doing our first paper back in 2019, we've witnessed the continued progress and evolution of the technology, including new use cases, such as fixed wireless access and indoor deployments, as well as new capabilities, such as 2 carrier uplink, not to mention performance enhancements. 5G mmWave is also no longer a US centric story. Our last paper included test results from Europe while this paper focuses on testing done in Tokyo, Japan.

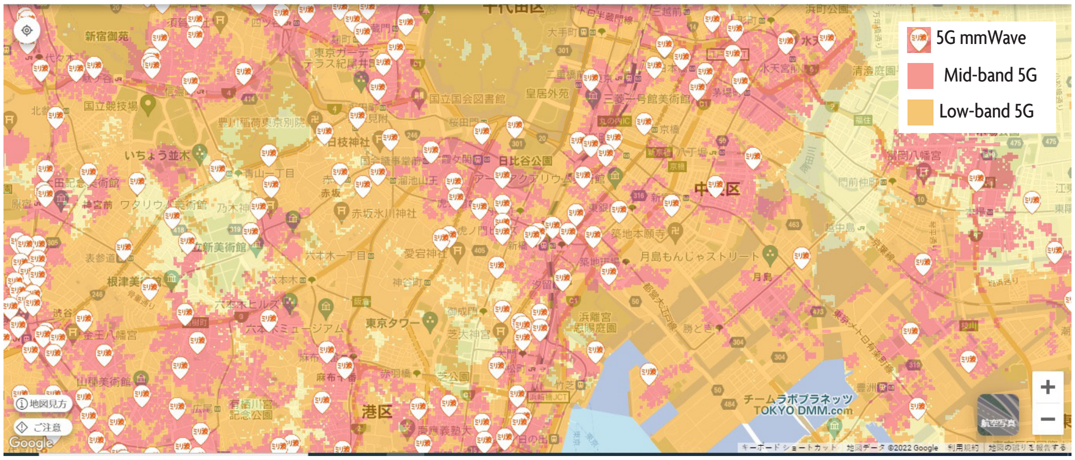
5G mmWave is alive and well in Tokyo, Japan

According to published reports, there are presently more than 20,000 5G mmWave sites spread across Japan. We didn't venture to Japan to validate this claim, but this data point is useful when put into context with the performance characteristics we documented. Furthermore, having tested multiple 5G mmWave cell clusters throughout downtown Tokyo, we can also offer a unique perspective on how and where operators are using 5G mmWave.

By and large, most of the 5G mmWave radios we observed were positioned on top of multi-story buildings. We also came across one site with the radios mounted on a street pole and one radio mounted just inside the entrance to Tokyo Station. From our perspective, the placement of the radios on top of buildings provided excellent coverage although it made it very difficult to spot the sites with the naked eye. Without companion coverage maps from the operators which show the general locations of the radios we would have never located many of them.

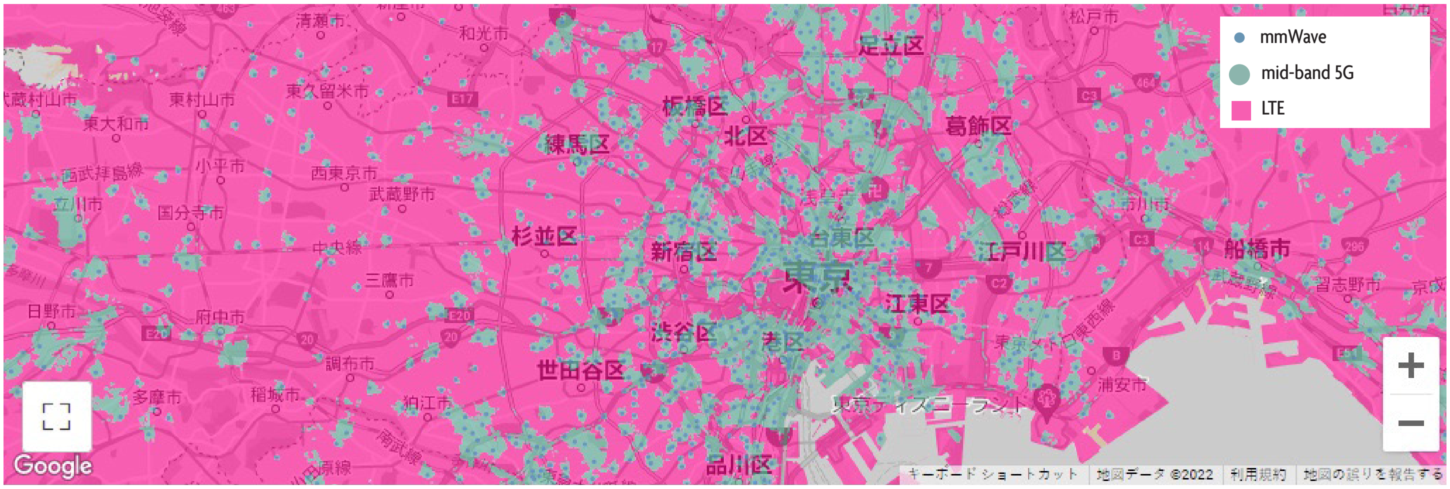
The next four figures provide 5G coverage maps for the four Japanese operators. All four figures show a healthy dose of 5G mmWave sites. For our testing, we concentrated on a select number of sites which we felt represented the overall market. We also included important or easily recognizable locations, such as commuter train stations and, of course, Tokyo Station.

Figure 1. KDDI 5G mmWave Coverage



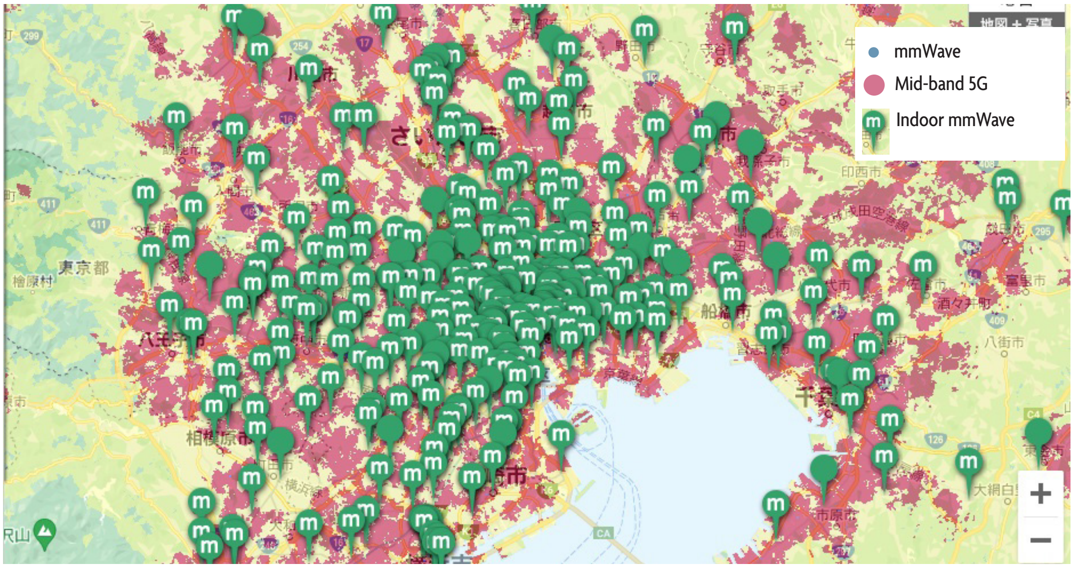
Source: KDDI Website

Figure 2. Rakuten 5G mmWave Coverage



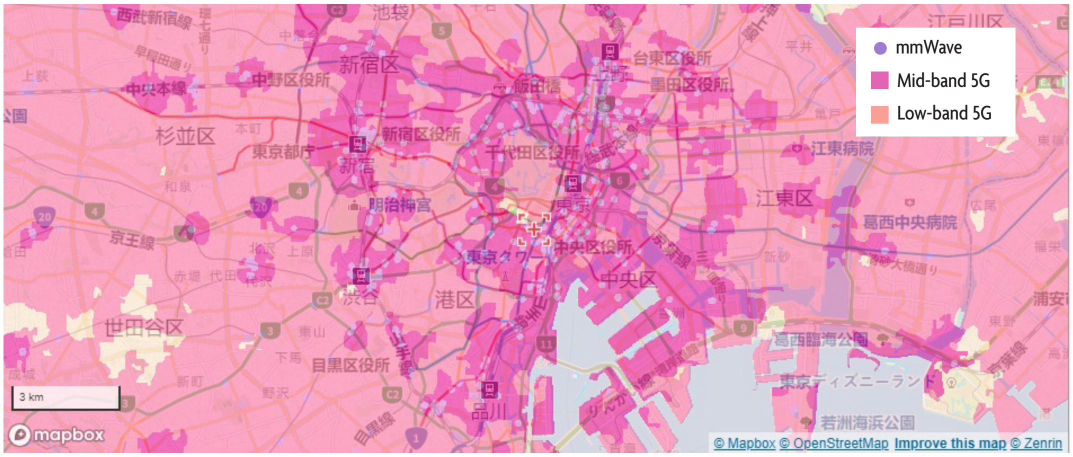
Source: Rakuten Website

Figure 3. NTT DoCoMo 5G mmWave Coverage



Source: NTT DoCoMo Website

Figure 4. Softbank 5G mmWave Coverage



Source: Softbank Website

Lastly, Figure 5 shows what we believe is a 5G mmWave radio belonging to one of the operators. This type of deployment is typical of what we observed in the city. By being deployed from a relatively high position, the 5G mmWave radios are able to provide extensive coverage along the wide streets, and in some cases extend both along the street where the radio is pointed as well as along the street perpendicular to the main road.

Figure 5. mmWave Radio Site

Source: Rakuten Website

5G mmWave uplink performance with carrier aggregation was quite impressive from a capacity and coverage perspective

We've used and tested 5G mmWave uplink performance numerous times in the past. We first tested 5G mmWave uplink carrier aggregation (2x100 MHz) in 2020. While we found the performance was good, it wasn't overwhelming, especially in comparison with the multi gigabit-per-second speeds that we are accustomed to observing in the downlink direction. In the testing we conducted in Tokyo, we found the uplink performance was stellar. In fact, we momentarily questioned the validity of the results we were observing on a real-time basis until we were later able to confirm the performance with a subsequent analysis of the log files.

In our 5G mmWave testing, it wasn't uncommon to observe 5G mmWave uplink throughput (PUSCH) reach 300 Mbps while we documented a peak uplink throughput of 326 Mbps – jumping to 370 Mbps with the LTE anchor cell providing additional uplink throughput thanks to the use of PDCP combining. In this example, we were located 115 meters from the serving cell site. Figure 6 puts things into perspective. Although it isn't visible in this picture, there is a 5G mmWave radio on the distant building, which according to our Google Earth calculations was 160 meters away from our location just outside of Tokyo Station where we observed 5G uplink throughput just above 300 Mbps, along with a downlink data speed just over 2 Gbps – the latter was obtained with only 400 MHz of spectrum.

We did a mix of stationary testing and walk testing as part of this benchmark study. For this paper, we are including the results from two different locations in Tokyo. We're including a multi-block area near the Shimbashi Train Station since we found extensive 5G mmWave coverage from multiple radios, not to mention from testing in this area we uncovered some optimization issues that we think are important to understand (discussed in a separate section). We're also including an area outside of Tokyo Station since in addition to being a well-known landmark in Tokyo, this area can be heavily congested with commuters and travelers entering and exiting the large transportation hub.

Figure 6. 300 Mbps Uplink @ 160 meters

Source: Signals Research Group

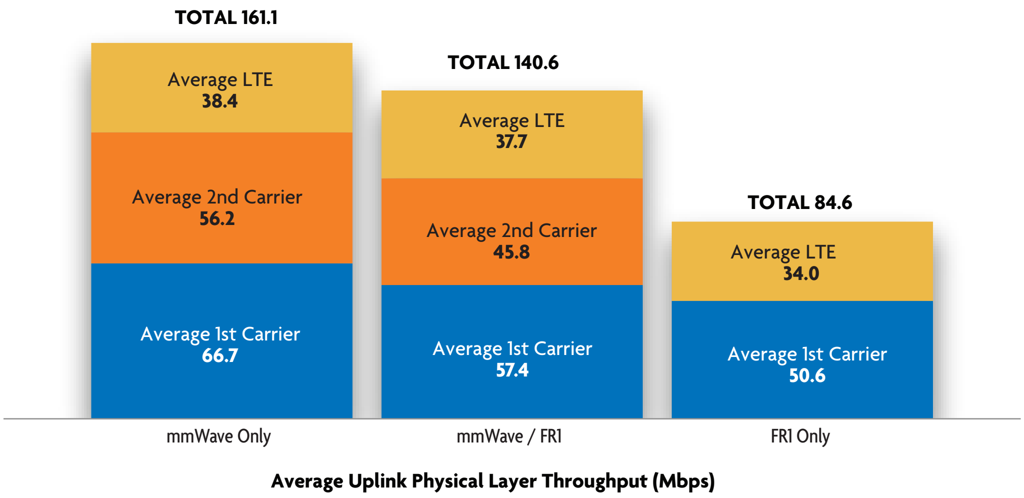
In the Shimbashi test area, we focused on stationary tests involving either downlink or uplink data transfers. We conducted two sets of tests. In the first set of tests, we selected random locations to capture 5G mmWave performance data and RF parameters, picking locations further and further away from the main area until the smartphone eventually dropped back to Band n78 coverage. We then repeated the tests but in this case we purposefully disabled 5G mmWave on the smartphone so the results from each test location reflected Band n78 performance. This approach allowed for good comparative results between the two frequency bands.

Figure 7 summarizes the results from this comparative testing. The figure shows three sets of results. The "FR1 Only" results provide the average uplink throughput (5G plus LTE) for those tests when we had disabled 5G mmWave on the smartphone. The middle set of results provide the results for all tests with 5G mmWave enabled on the smartphone. Since these tests included results from locations where 5G mmWave wasn't available we've labeled the results "mmWave/FR1" – the results from locations where the smartphone was limited to FR1 are included in the Average 1st Carrier result. Finally, with the "mmWave Only" results, we only included those test locations when the smartphone used 5G mmWave (i.e., we excluded those test results when the smartphone fell back to mid-band 5G. Put another way, the "mmWave Only" results reflect a subset of the "mmWave/FR1" results.

5G mmWave increased uplink throughput by more than 2x when compared with the mid-band 5G uplink results.

Including the contribution from LTE, the network support for 5G mmWave increased uplink throughput by 1.7x to 1.9x, depending on which set of results is used to compare with the FR1 Only results. If the comparison is done strictly between the two 5G frequencies, then mmWave increased uplink data speeds by more than 2x versus FR1 Only with the second component carrier accounting for just under half of the total uplink throughput. The pending introduction of 4-carrer uplink functionality will further widen the performance gap between mmWave and mid-band 5G.

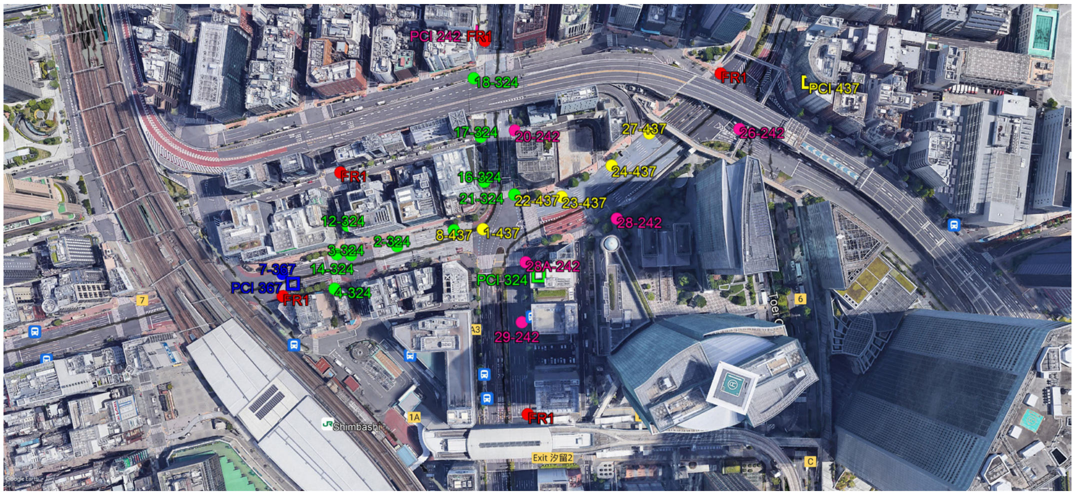
Figure 7. Uplink Stationary Test Results



Source: Signals Research Group

Now that we've summarized the main results from the uplink testing in this area, we provide some additional insight into the test results from this cluster of 5G mmWave cells. Figure 8 provides a map of the test area, showing the locations of four 5G mmWave cell sites as well as each test location. The cell site locations are depicted by a colored square icon and labeled PCI XXX (Physical Cell Identity). We labeled each test location with the test ID number and the cell PCI value the smartphone used during the test. For simplicity, we also color coded each test location to map it to the corresponding cell site (i.e., all test locations where the smartphone attached to PCI 437 are colored yellow). Although it isn't shown in the figure, there were at least two 5G mmWave radios on the opposite side of the train station and we captured a few additional 5G mmWave PCI values in the log files – we still have no idea where those 5G mmWave sites were located. As a frame of reference, PCI 437 is approximately 440 meters away from the train station.

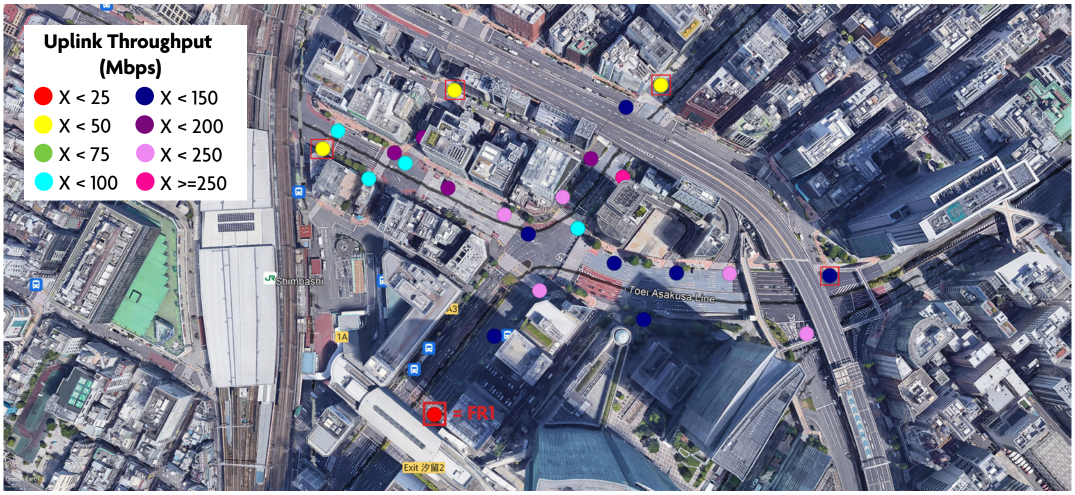
Figure 8. 5G mmWave Cell Site and Uplink Stationary Test Locations



Source: Signals Research Group

Figure 9 provides a map of the average throughput, including the individual contributions from 5G and LTE, from each test location. The cell sites where the smartphone used Band n78 have a red rectangle over the throughput result.

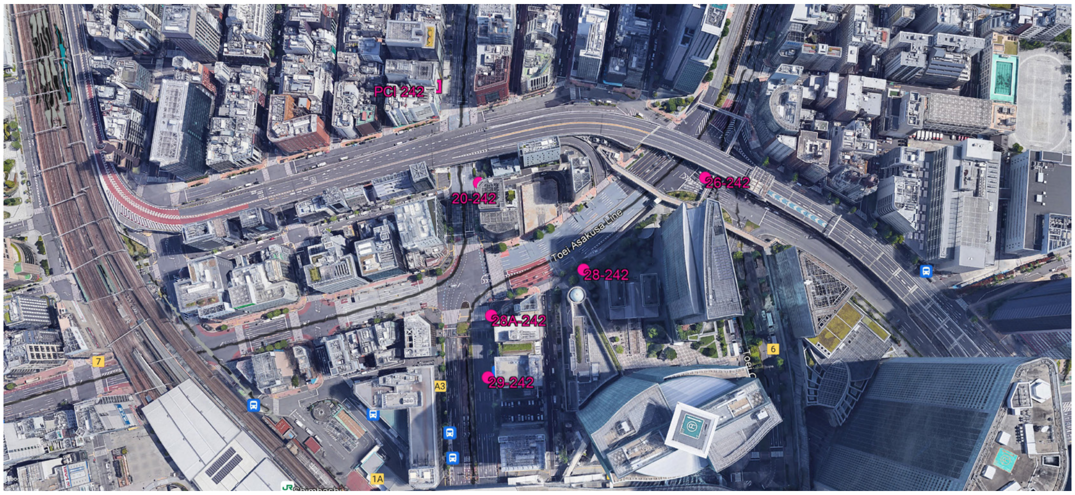
Figure 9. 5G mmWave Uplink Throughput Results



Source: Signals Research Group

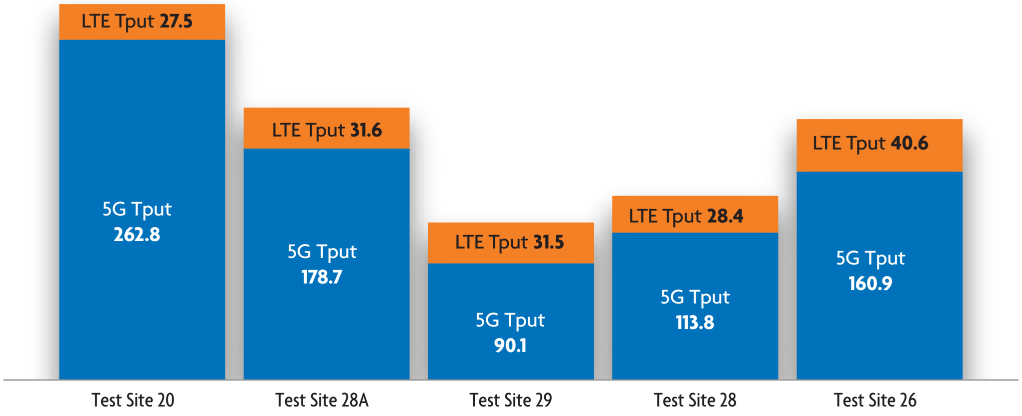
For additional clarity, the next set of figures show uplink throughput results at the selected test locations for three 5G mmWave sites. Figure 10 and Figure 11 show results for PCI 242. As one might expect, test locations further away from the serving cell had lower throughput. It is noteworthy that this cell site provided coverage along portions of two major streets that were perpendicular to each other.

Figure 10. 5G mmWave Uplink Test Locations – PCI 242



Source: Signals Research Group

Figure 11. 5G mmWave Uplink Throughput Results – PCI 242

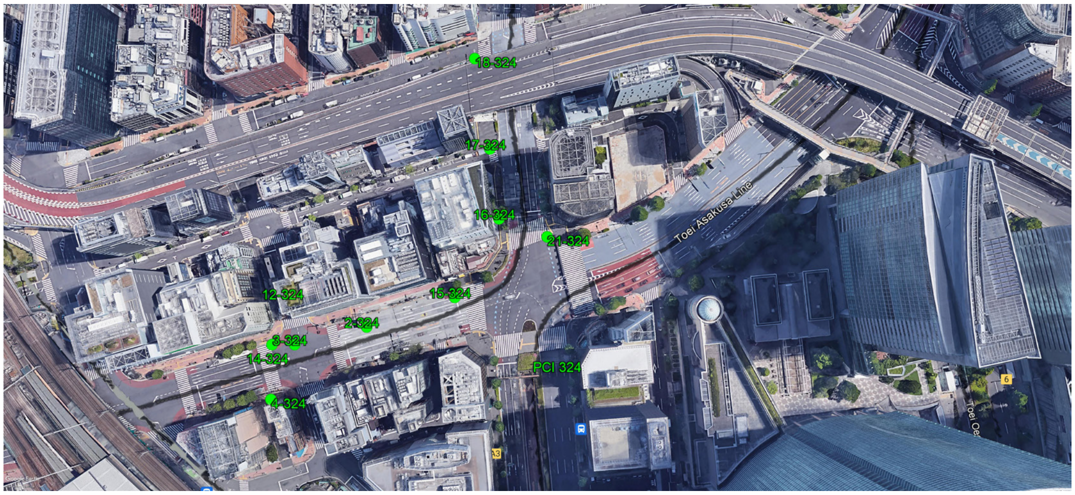


Mbps

Source: Signals Research Group

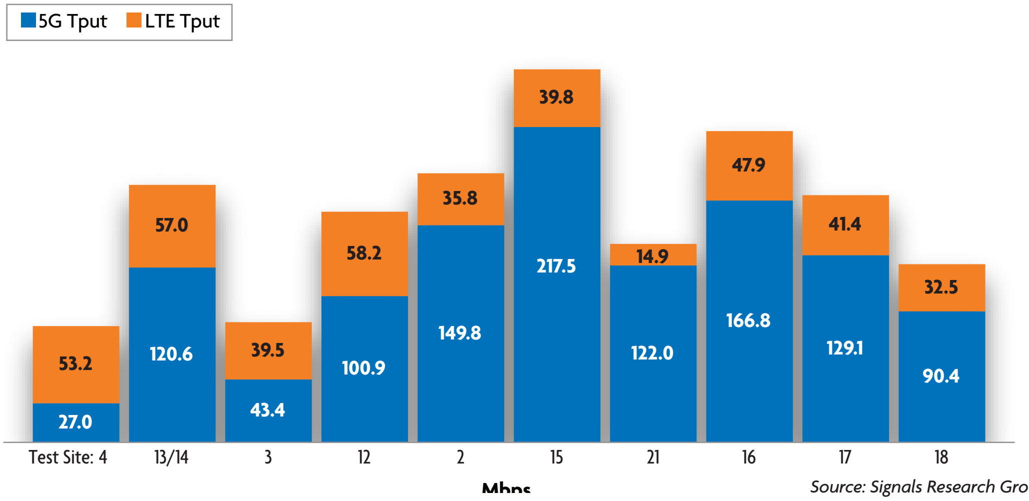
Figure 12 and Figure 13 show similar information for PCI 324. Like what we observed with PCI 242, this cell site provided coverage along two perpendicular streets. Additionally, by comparing Figure 12 and Figure 10 it is evident that the coverage offered by the two 5G mmWave sites overlapped each other. In the case of test location 18, the location was actually much closer to PCI 242, but the smartphone attached to PCI 324.

Figure 12. 5G mmWave Uplink Test Locations – PCI 324



Source: Signals Research Group

Figure 13. 5G mmWave Uplink Throughput Results – PCI 324



Source: Signals Research Group

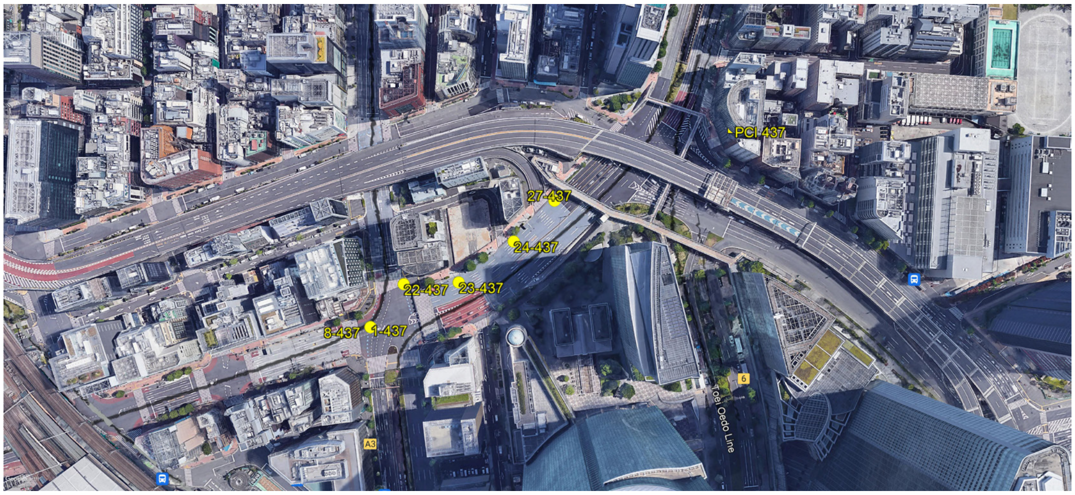
Figure 14 provides a view toward the direction of the serving cell site from test location 18. It is very evident in the picture that the overpass was blocking the view of the 5G mmWave radio, which was located on top of the building. The upward facing red arrow points to the location of the 5G mmWave radio, which is clearly hidden from view.

Figure 14. A View of PCI 324 From Test Location 18

Source: Signals Research Group

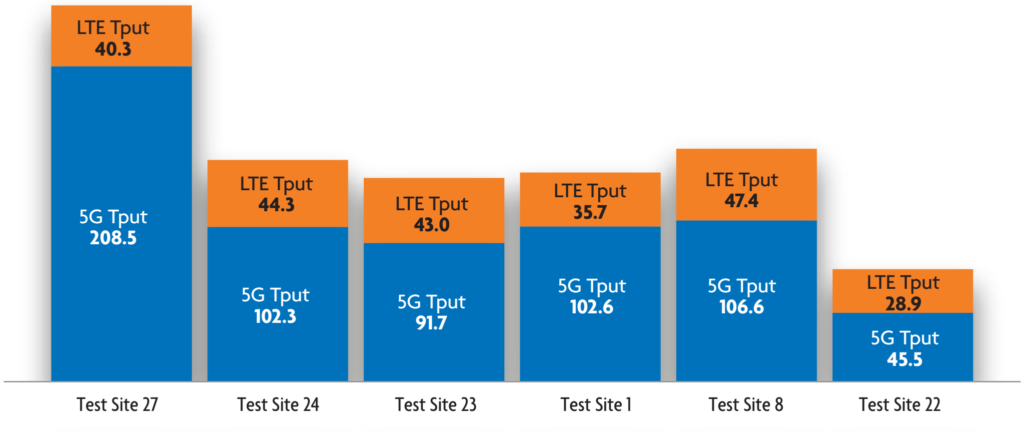
Finally, Figure 15 and Figure 16 show the results for PCI 437.

Figure 15. 5G mmWave Uplink Test Locations – PCI 437



Source: Signals Research Group

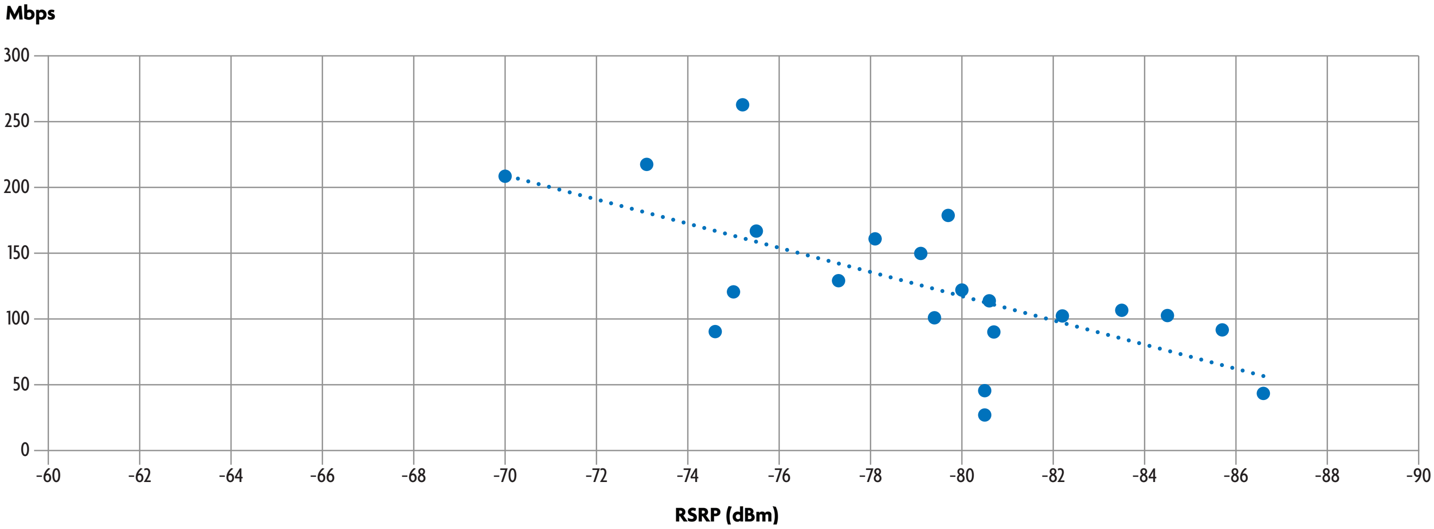
Figure 16. 5G mmWave Uplink Throughput Results – PCI 437



Source: Signals Research Group

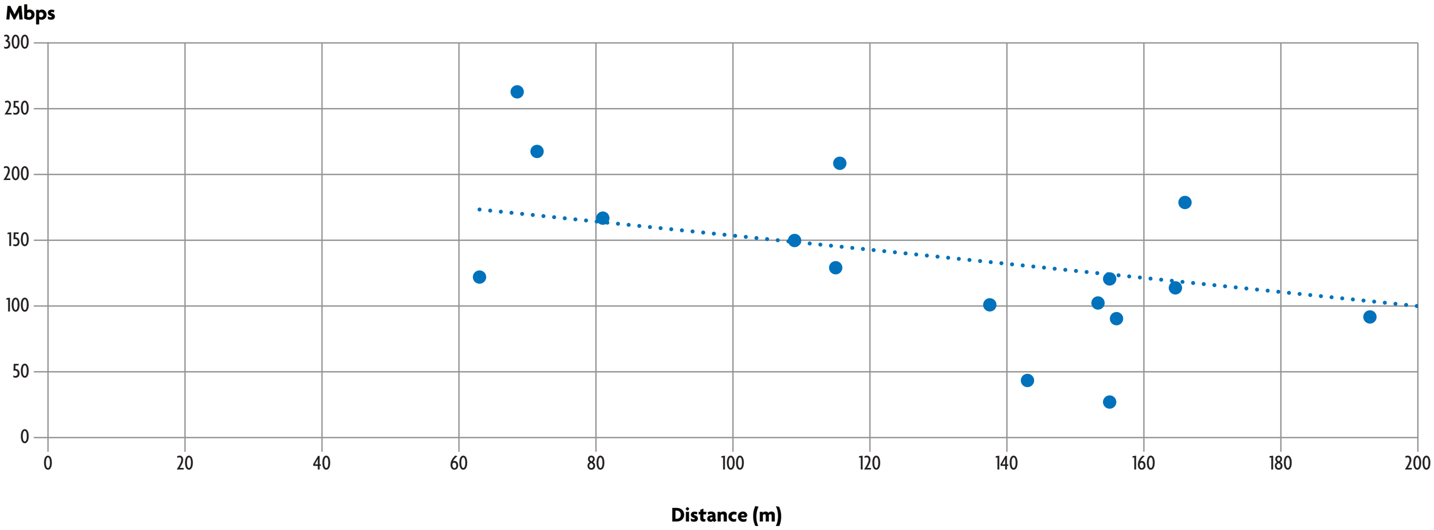
The next three figures show the relationships between distance, uplink throughput and signal strength, or RSRP. Figure 17 plots the uplink throughput as a function of the RSRP and Figure 18 shows the uplink throughput versus the distance to the cell site. Lastly, Figure 19 plots the RSRP as a function of the distance to the cell site. There is a reasonably good correlation between the uplink throughput and RSRP while the other figures exhibit only a modest correlation (i.e., the throughput or RSRP drops with increasing distance).

Figure 17. 5G mmWave Uplink Throughput Versus RSRP



Source: Signals Research Group

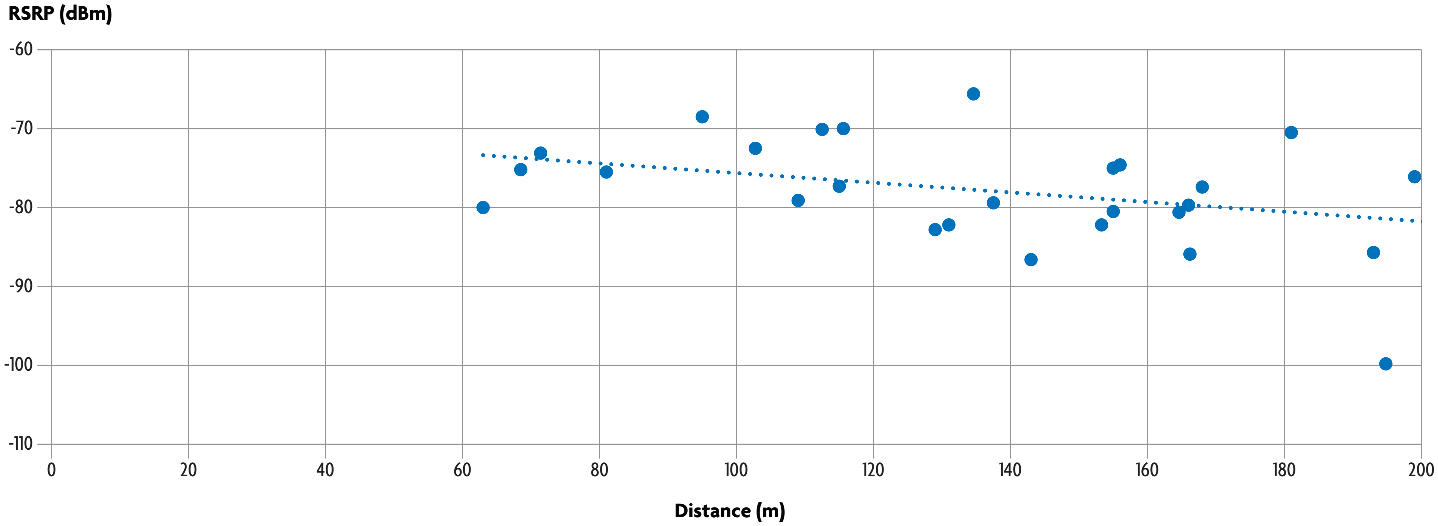
Figure 18. 5G mmWave Uplink Throughput Versus Distance



Source: Signals Research Group

It isn't surprising there is only a slight correlation between RSRP/throughput and distance since other factors, such as line-of-site (LOS) versus non-line-of-site (NLOS) have an impact, just as the test location in relation to the direction the mmWave radio is facing has an impact – all things being equal, being off angle will degrade the signal strength and throughput relative to being directly in-line with the direction the radio is facing. Nonetheless, we can conclude that achieving an uplink throughput of 100 Mbps at a distance of 200 meters is entirely possible, as is achieving an uplink throughput of more than 200 Mbps at a distance of 100 meters. Depending on transmit power limitations, even higher data speeds are possible with the pending introduction of 4-carrier uplink functionality.

Figure 19. 5G mmWave RSRP Versus Distance



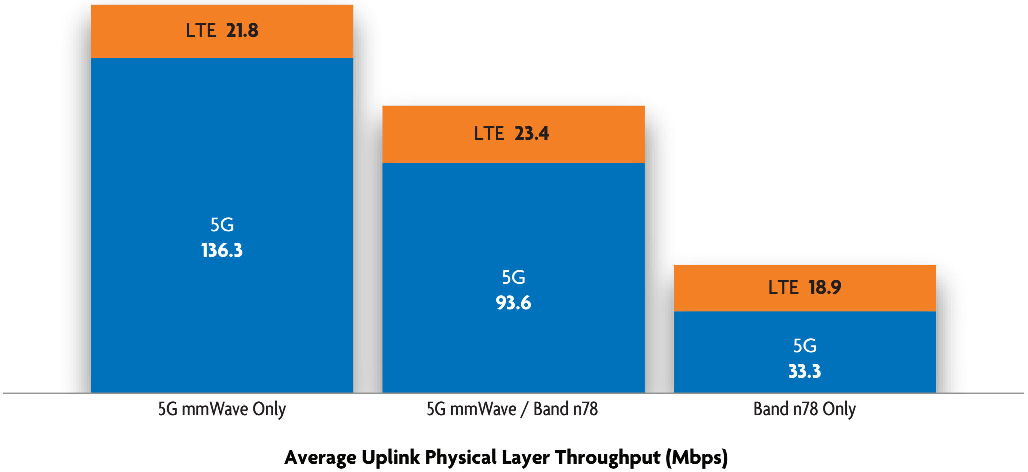
Source: Signals Research Group

We now head a few kilometers north to Tokyo Station where we did a comparative uplink walk test between 5G mmWave and Band n78. For these tests we walked outside of the station in an area where commuters and travelers congregate to catch a bus or taxi or where they get dropped off at the station – we revisited this location when our taxi driver dropped us off for the train ride out to the Narita airport at the end of our visit. We identified two 5G mmWave radios covering this area, including the cell site shown earlier in Figure 6. During one walk, the smartphone was configured to support both 5G mmWave and mid-band 5G, while in the second walk, we configured the smartphone so that it only supported mid-band 5G.

The 5G uplink throughput was 2.8x higher during the walk when the smartphone supported 5G mmWave.

Figure 20 shows the results of these two tests. The "Band n78 Only" result provides the 5G and LTE throughput during the walk when the smartphone only supported Band n78. The other two columns show the 5G and LTE uplink throughput when the smartphone supported 5G mmWave. In the "5G mmWave Only" bar, we only included those instances when the smartphone was using 5G mmWave, while the middle bar shows results from the entire walk test, including those times when the smartphone fell back to mid-band 5G. The 5G uplink throughput was 2.8x higher during the walk when the smartphone supported 5G mmWave, or 4.1x higher during the same walk if we only include those times when the smartphone used 5G mmWave.

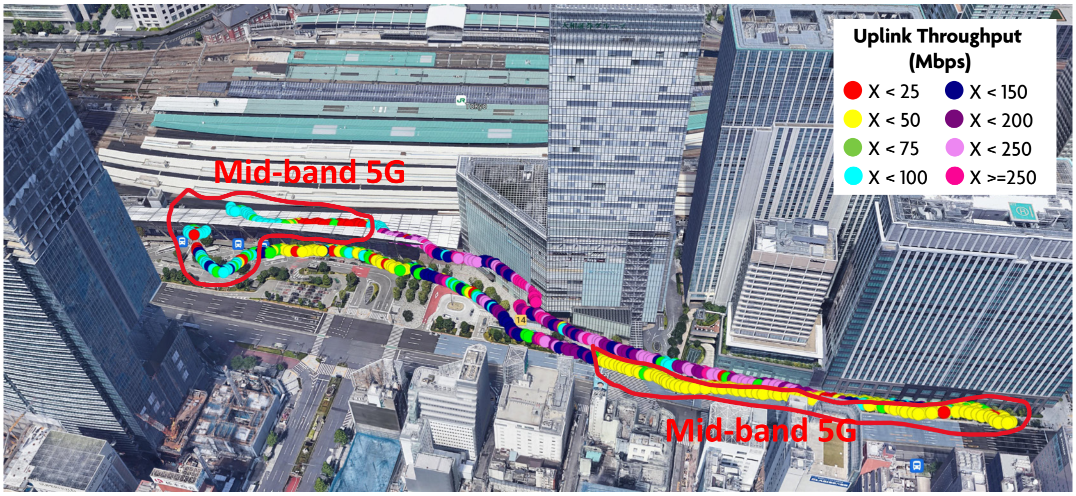
Figure 20. Uplink Walk Test Results



Source: Signals Research Group

Figure 21 provides a geo plot of the uplink throughput (LTE + 5G) when the smartphone supported 5G mmWave. We've circled those areas during the walk when the smartphone was only using mid-band 5G, or on the far left and far right side of the figure. It is evident that when we walked back into 5G mmWave coverage on the right side of the image that the smartphone remained on mid-band 5G for an extended period of time, even though 5G mmWave was available (note the yellow circles located immediately alongside the other colored circles illustrating much higher throughput when the phone was using 5G mmWave.

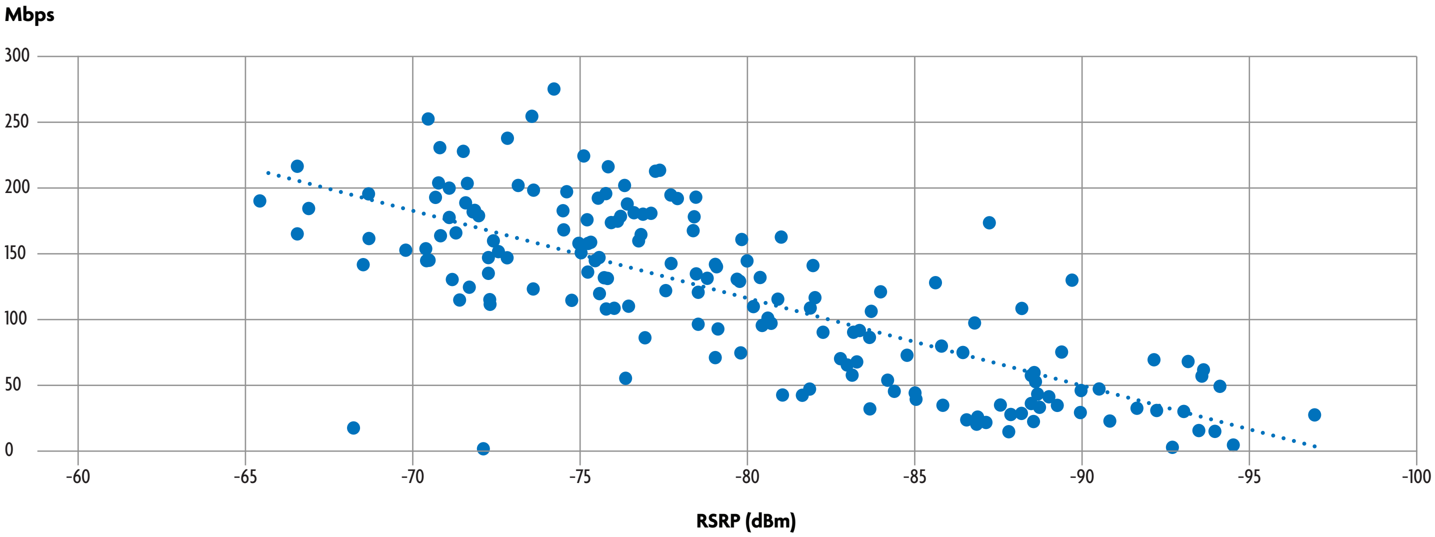
Figure 21. Uplink Throughput



Source: Signals Research Group

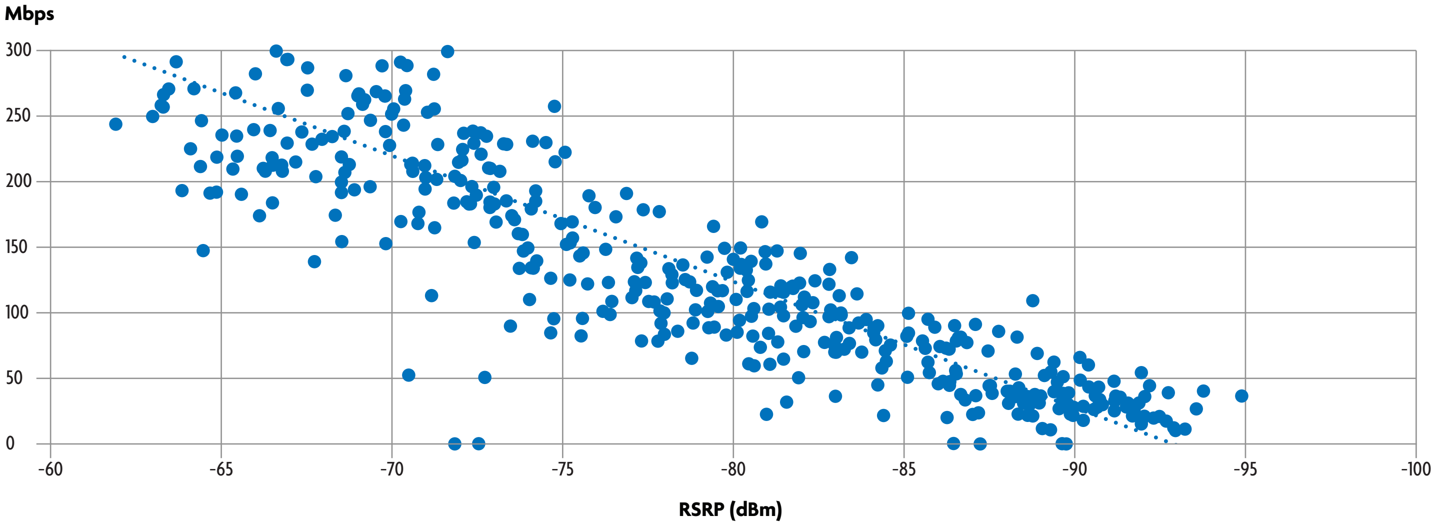
Figure 22 and Figure 23 show the relationship between uplink throughput and RSRP for the two 5G mmWave radios encountered during the walk. In both figures there is reasonably good correlation between the two metrics. We suspect the ~0 Mbps values obtained with relatively high RSRP stem from instances when the data session used to generate the uplink data transfers had finished. However, we elected to keep these values in the figure to refrain from injecting any bias into the analysis.

Figure 22. Uplink Throughput versus RSRP – PCI 225



Source: Signals Research Group

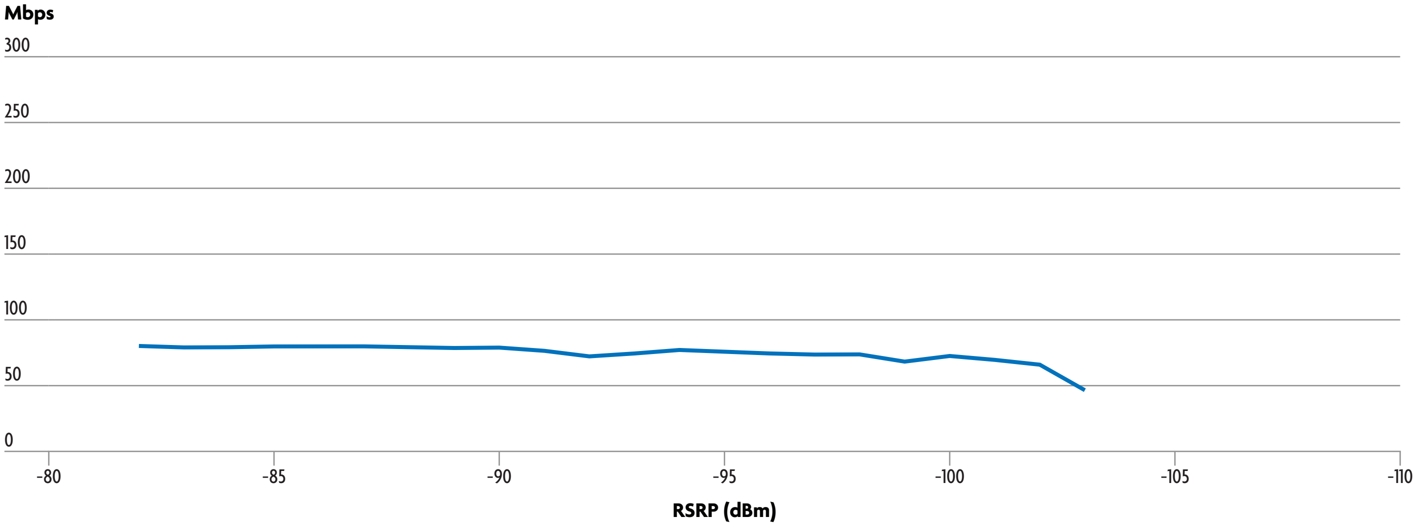
Figure 23. Uplink Throughput versus RSRP – PCI 200



Source: Signals Research Group

Figure 24 shows the results with 5G mmWave disabled in the smartphone. We've intentionally left the Y axis scale unchanged from the mmWave results to highlight the large differences in the observed uplink throughput between the two frequency bands. In this test, and in much of our testing in Tokyo, the uplink throughput using Band n78 was almost always greater than 50 Mbps and frequently near 70 Mbps, peaking at 80 Mbps. We attribute the outcome to light loading in the uplink direction.

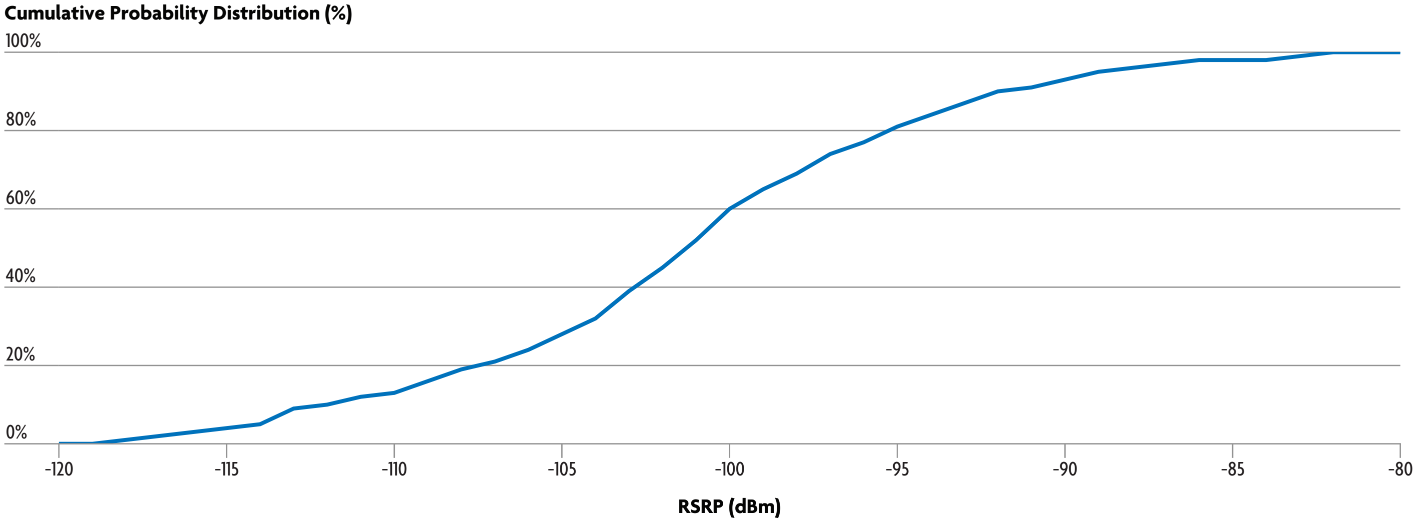
Figure 24. Uplink Throughput versus RSRP – Band n78



Source: Signals Research Group

Figure 25 provides the RSRP distribution for Band n78 during this walk test. Interestingly, the RSRP distribution wasn't entirely favorable – 40% of the time the RSRP was at or below -100 dBm.

Figure 25. Distribution of Band n78 RSRP

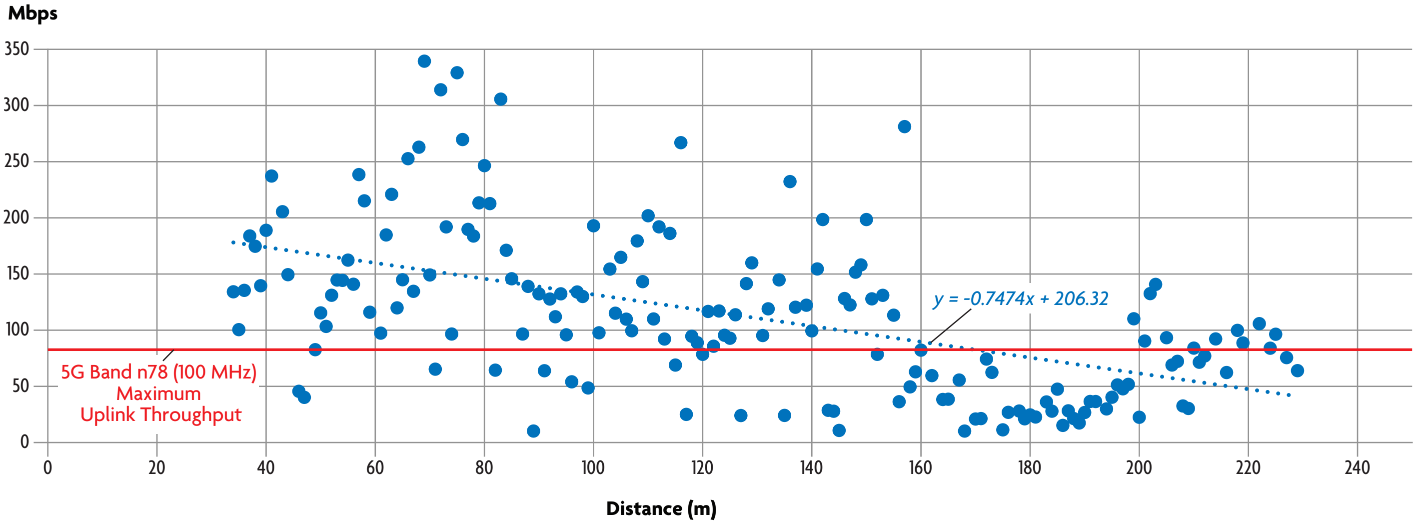


Source: Signals Research Group

There is a very good chance the uplink throughput on 5G mmWave will exceed that of mid-band 5G spectrum.

We weren't able to identify the locations of the Band n78 radios, so we are not able to provide any analysis involving distances to the serving cell site. However, since we could locate the 5G mmWave radios – the operator's mmWave coverage map definitely helped – we can show the relationship between 5G mmWave uplink throughput and distance, as shown in Figure 26. Although the correlation is great, due to reasons previously discussed in this section – we can observe that in this case 50 Mbps of uplink throughput is very possible at a distance of 200 meters or 75 Mbps at a distance of 175 meters. Put another way, at distances up to 200 Mbps from the cell site, there is a very good chance the uplink throughput on 5G mmWave will exceed that of mid-band 5G spectrum while at closer distances the performance advantage will be even more significant. Even if mid-band 5G achieves higher throughput than mmWave, there is still the need for additional capacity that mid-band 5G can't provide. Keep in mind, the uplink results collected for this study occurred on a very lightly-loaded network (uplink) and that any loading on the mid-band network will only serve to lower the achievable end user data speeds.

Figure 26. 5G mmWave Uplink Throughput versus Distance



Source: Signals Research Group

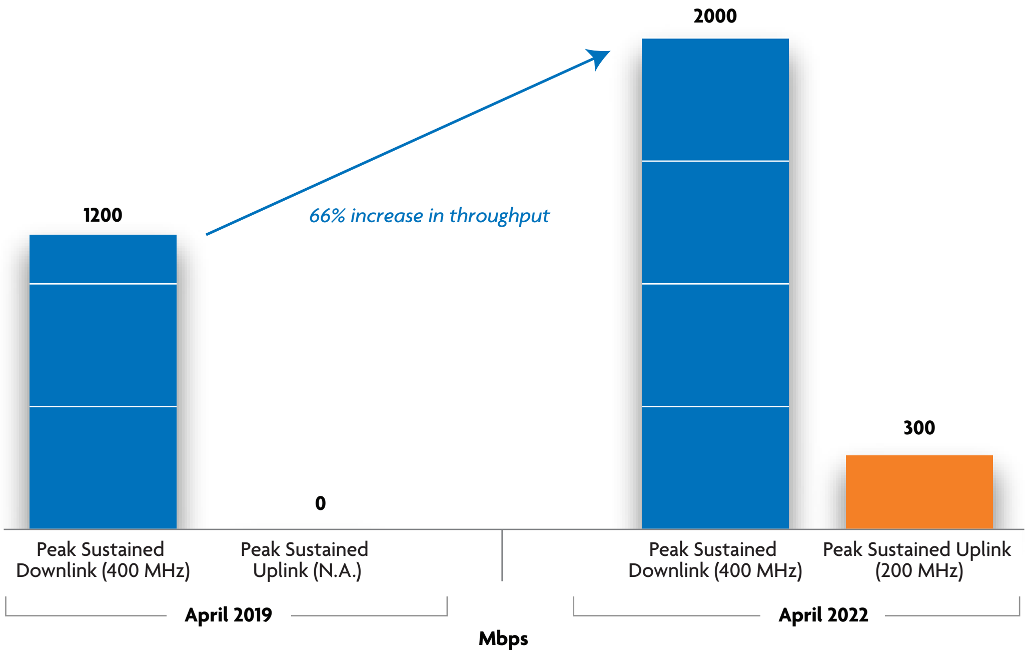
5G mmWave has achieved considerable gains in downlink spectral efficiency since its inception

Operators in Japan currently have only 400 MHz of 5G mmWave spectrum (Band n257) so inherently the maximum downlink data speeds were much lower than we've observed while testing in the United States and Europe. However, from our testing it was very clear that from the perspective of spectral efficiency, or how much total throughput can be achieved for a given amount of spectrum, there have been tremendous gains in 5G mmWave performance since the first tests we conducted back in April 2019. During those initial tests, the networks were also limited to only 400 MHz, but they have since increased to 800 MHz due to the evolution of 5G mmWave infrastructure and chipsets.

Over a period of three years, there has been a 66% increase in the maximum sustained downlink data speeds over 5G mmWave.

It isn't practical to compare average data speeds between what we observed in Tokyo versus what we've witnessed in other markets, largely because the environments where the networks were deployed are different and because operators have different philosophies on where to install the 5G mmWave radios. However, it is possible to compare maximum sustained data speeds, as we have done in Figure 27. The figure includes two sets of results – one from our most recent testing and one from testing that we did on the Verizon network back in April 2019. The figure shows the maximum downlink throughput that we observed on a sustained basis on the two networks, both comprised of 400 MHz of spectrum (4x100 MHz). Over a period of three years, there has been a 66% increase in the maximum sustained downlink data speeds over 5G mmWave. Further, although it isn't reflected in the figure, we can now observe the peak downlink data speeds at much greater distances than possible back in April 2019. The figure also includes information on the gains in uplink performance, which can't be directly compared because in April 2019 all the uplink data traffic went over LTE.

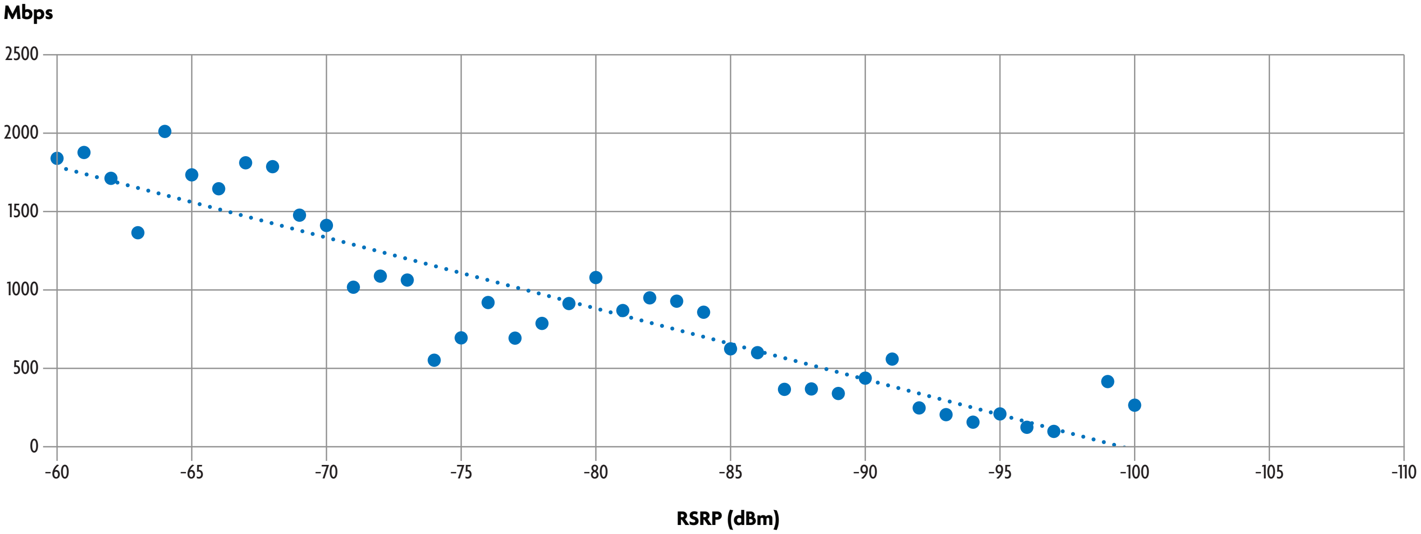
Figure 27. 5G mmWave Downlink Performance Gains



Source: Signals Research Group

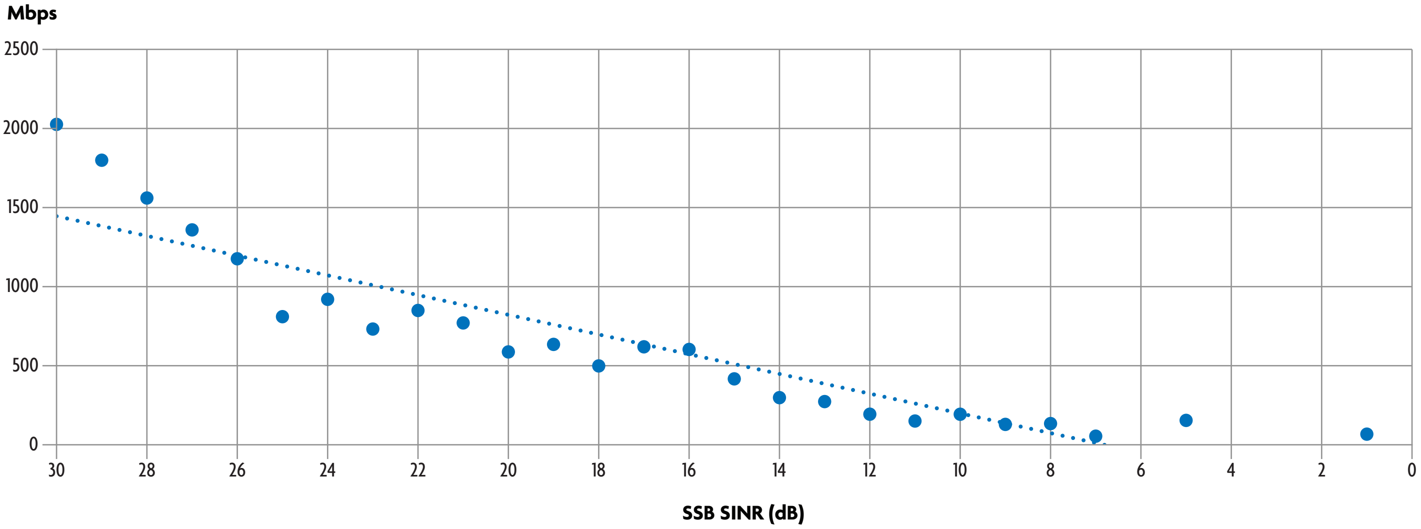
The next two figures show the relationships between downlink 5G PDSCH throughput and RSRP (Figure 28), or between downlink 5G PDSCH throughput and SSB-SINR (Figure 29). We point out that each circle represents an average of all measured throughput data points for that corresponding RSRP/SINR value. Further, there is also the LTE contribution to total user throughput which is not included in the figures. Both figures show a relatively strong correlation between throughput and RSRP/SSB-SINR.

Figure 28. 5G mmWave Downlink Throughput Versus RSRP



Source: Signals Research Group

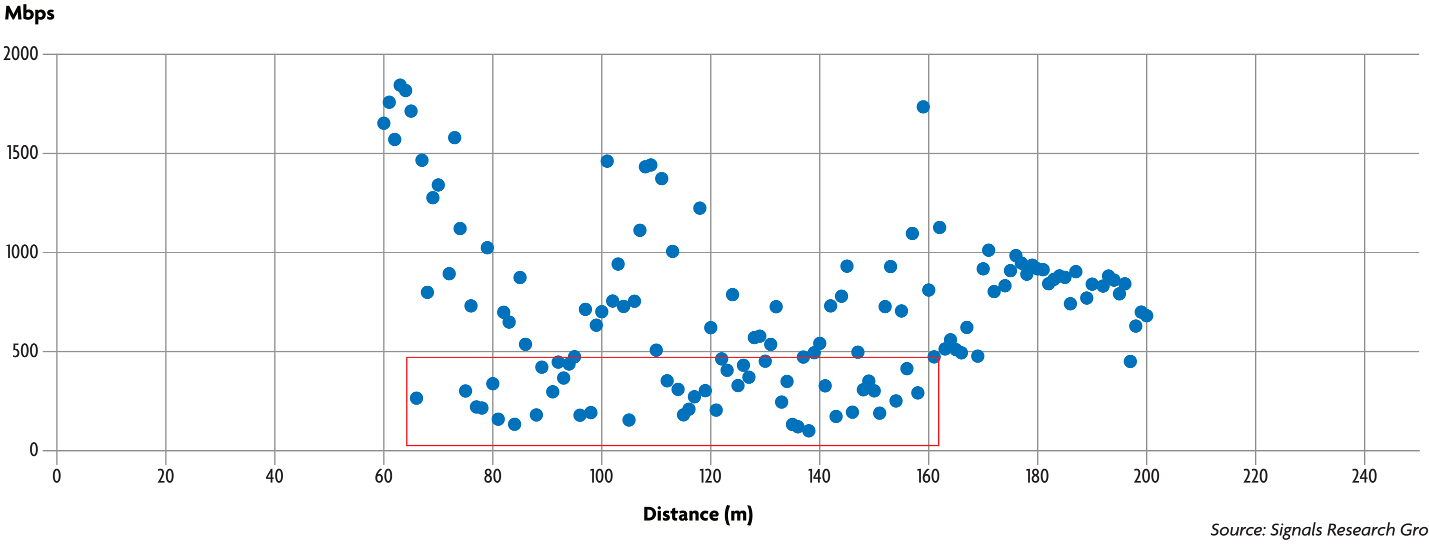
Figure 29. 5G mmWave Downlink Throughput Versus SINR



Source: Signals Research Group

Figure 30 shows the impact of distance on the 5G PDSCH downlink throughput. Much like we showed with the uplink data throughput, there wasn't a strong correlation between the two sets of data. In the figure, we also highlighted several data points which show relatively low throughput for the distance involved. We believe these low data points represent an opportunity for additional network optimization, and it is something we discuss in the next section.

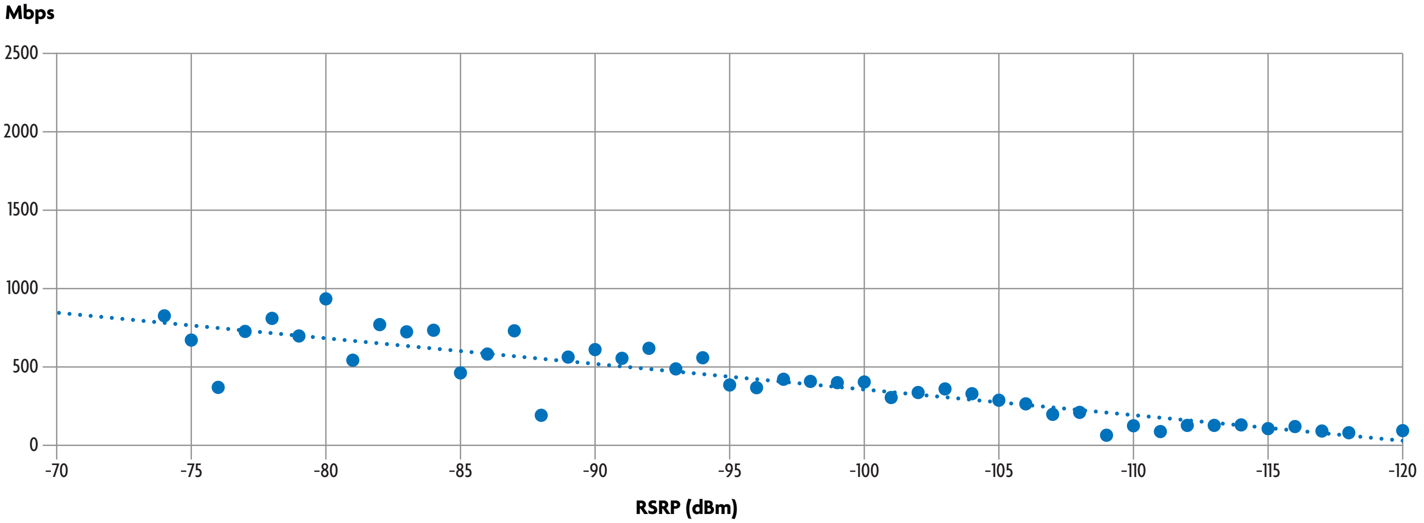
Figure 30. 5G mmWave Downlink Throughput Versus Distance



Source: Signals Research Group

Lastly, Figure 31 shows the relationship between Band n78 downlink throughput and the RSRP. These test results stem from testing in another location in Tokyo. We left the Y axis unchanged from the 5G mmWave results to emphasize the large differences in throughput between the two frequency bands.

Figure 31. 5G Band n78 Downlink Throughput versus RSRP



Source: Signals Research Group

Further gains in the 5G mmWave performance we observed in Tokyo are readily possible

When we were collecting performance data on the mmWave networks in Tokyo, we observed some throughput anomalies that we subsequently investigated further after completing all the testing. Based on our analysis of the data, we identified a few opportunities for additional network optimization which could meaningfully improve the strong results we obtained. Furthermore, one of the areas for optimization had nothing directly to do with the mmWave aspect of the network, but instead had to do entirely with the underlying LTE network, which provided the anchor cell for the 5G network.

When testing in the vicinity of the Shimbashi Train Station we noticed two phenomena. First, the smartphone "lost" the 5G mmWave connection on a repetitive basis in areas where we knew there was 5G mmWave coverage. Toggling the phone into and out of airplane mode generally caused the smartphone to reattach to the 5G mmWave network. Second, the throughput in this area during walk tests was more erratic than we are used to seeing. Instantaneous physical layer throughput on any cellular network, including LTE, is far more variable than most consumers realize – a simple measurement with the Speedtest application merely captures the average over the measurement period and it doesn't reveal the variability in the throughput during the test. However, in this case the variances in the throughput we were observing with our logging tools was far more than we anticipated, especially given the favorable network conditions. We later attributed this issue to the LTE network, as shown in subsequent figures.

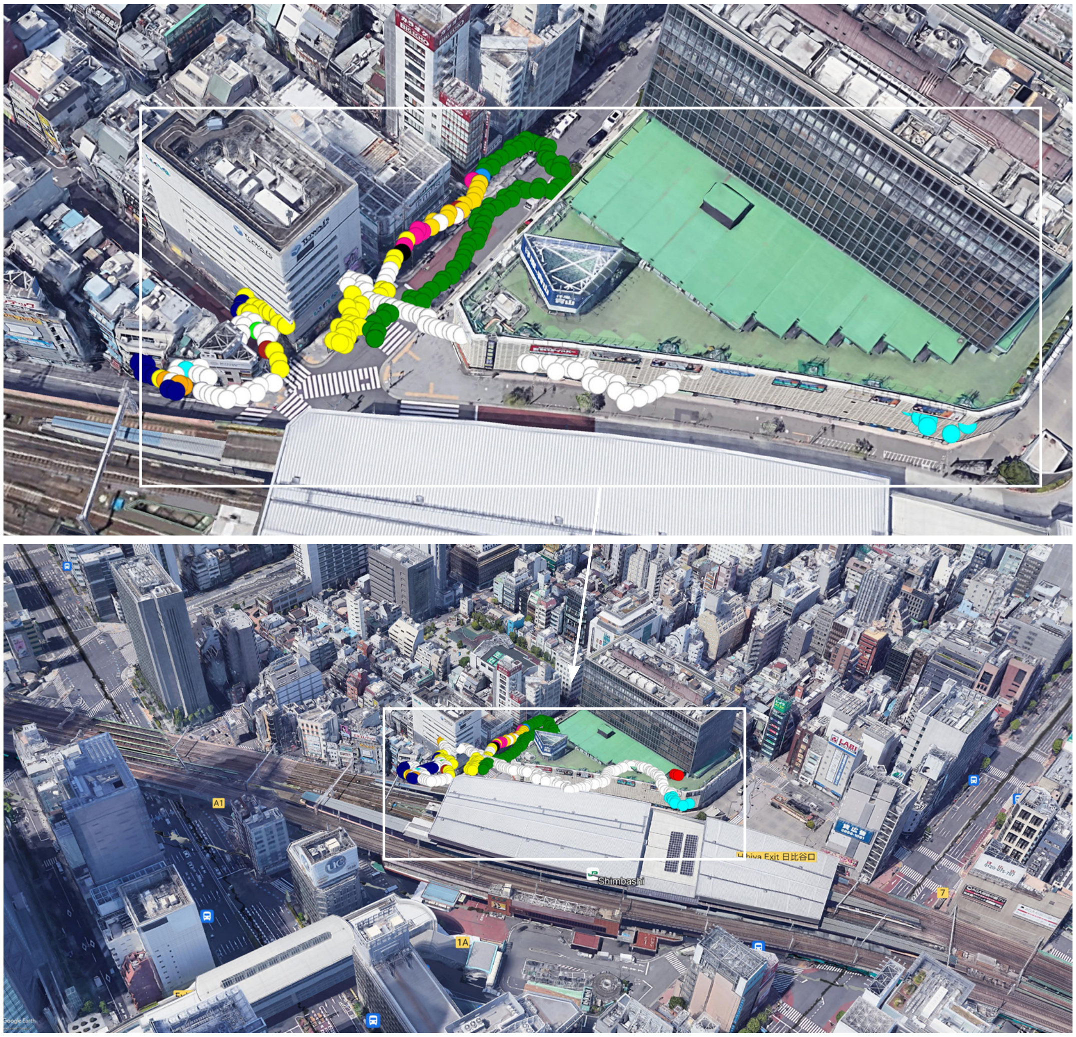
Based on our analysis of the data, two related events were occurring. First, the smartphone was frequently handing off between different LTE cells (PCI values), either involving different PCIs at different physical location, or the same physical location but with a different carrier frequency. Although many of the LTE PCI values were mapped to the 5G mmWave radio in the area, not all of the PCI values were correctly mapped.

We point out that with the NSA (Non Standalone) architecture, there is an LTE anchor cell that is required in addition to the 5G radio. In order for the network to enable EN-DC (Evolved UTRA – Dual Connectivity), or the 5G connection supported by the LTE radio bearer, the LTE radio needs to be associated with the 5G mmWave radio and it needs to communicate this information to the mobile device. The EN-DC requirements exists for low-, mid- and 5G mmWave, but the requirement is most likely to cause an issue with 5G mmWave due to the size of the coverage when compared with an LTE cell site. Put another way, at many locations in a network there can be a multitude of available LTE PCIs that a smartphone can attach to, albeit momentarily. If a smartphone happens to attach to an LTE PCI that isn't associated with the nearby 5G cell site, then the smartphone won't attach to 5G.

In some of our initial testing of 5G mmWave we experienced this issue fairly often. In fact, we first noticed the issue when we were walking directly toward a 5G mmWave radio that was well within coverage. After some investigation on our part, we observed that each time the smartphone dropped the 5G mmWave connection, it occurred in conjunction with an LTE handover. This "issue" is easily addressed, and the problem has nothing directly to do with mmWave performance, but it is something that an operator needs to include as part of the network optimization activities.

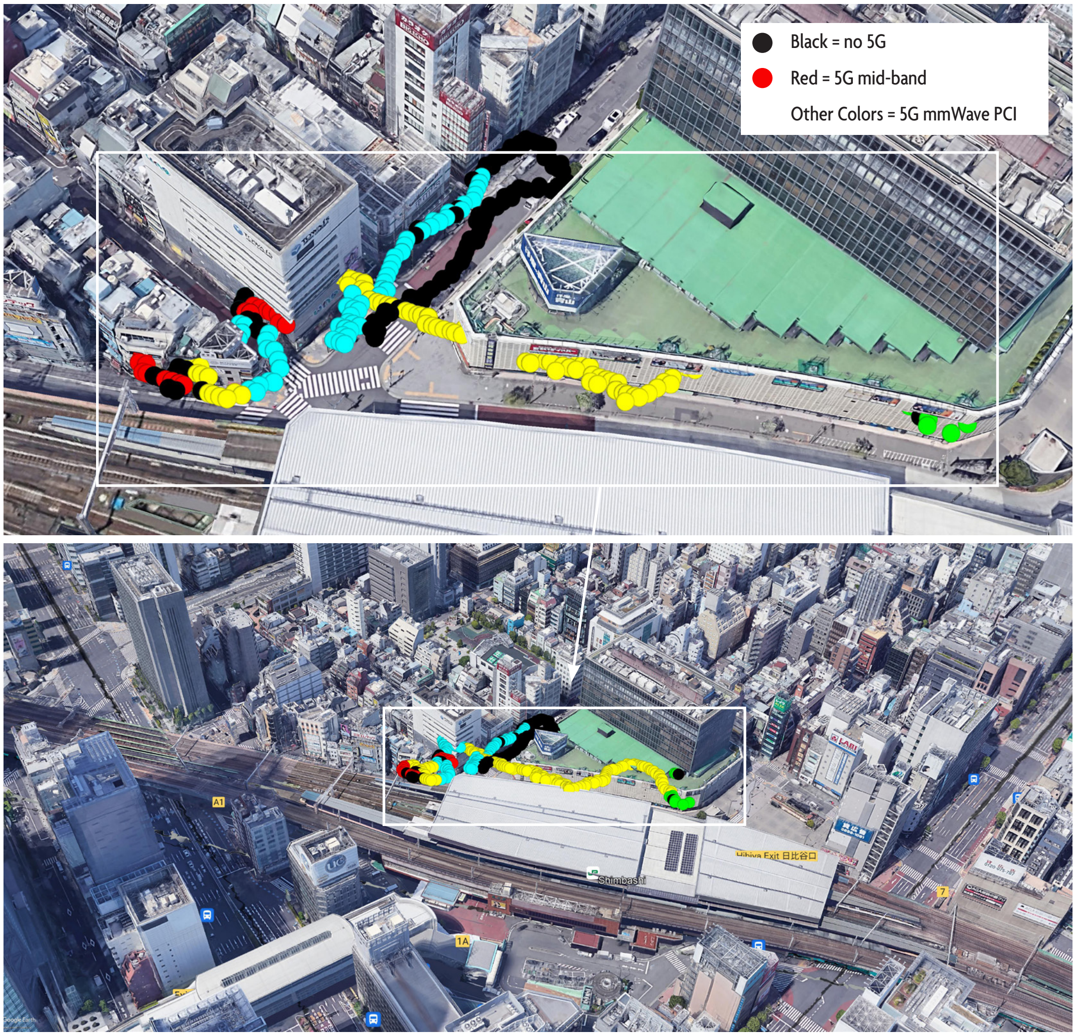
Figure 32 provides a geo plot of the LTE serving cell during a downlink walk test near the Shimbashi Train Station. Each unique colored circle in the figure identifies a different LTE anchor cell that the smartphone was using at that location. Figure 33 provides similar information for the 5G PCIs. Comparing the two figures, it is evident that when the smartphone was using LTE PCI = 294 (depicted by Green circles in Figure 32), the smartphone never used 5G mmWave (many of the black circles in Figure 33) even though it was obviously available in the vicinity.

Figure 32. LTE PCI Map



Source: Signals Research Group

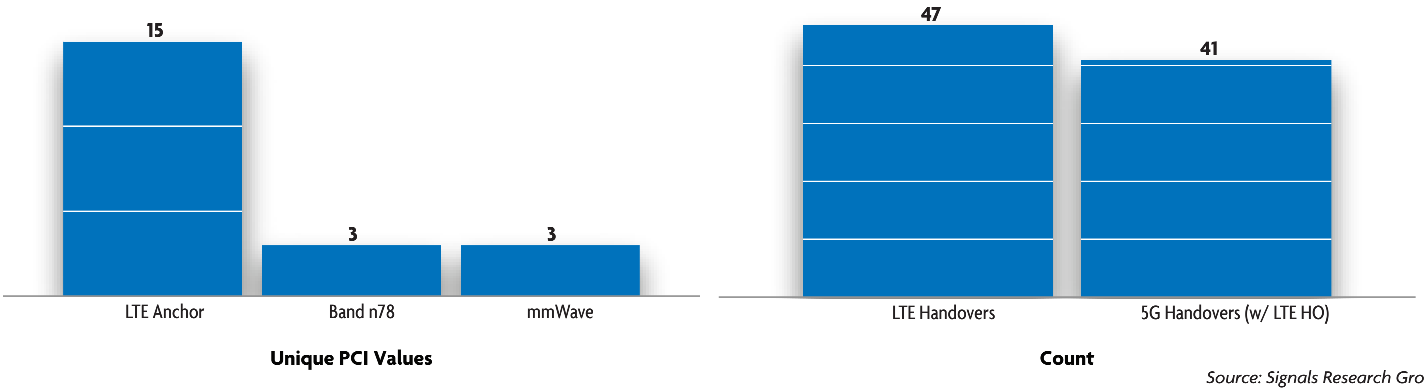
Figure 33. 5G mmWave PCI Map



Source: Signals Research Group

As a frame of reference, during this walk test the smartphone attached to 15 unique LTE PCI values. It only used 3 different 5G mmWave PCI values and 3 different Band n78 PCI values – from our analysis of the underlying data the smartphone rarely needed to drop back to mid-band 5G since the 5G mmWave coverage was generally sufficient. Instead, the smartphone selected mid-band 5G because the mapping of LTE and 5G mmWave PCIs was not complete. Figure 34 graphically shows the cell and handover counts for LTE, mid-band 5G, and 5G mmWave. It is worth highlighting that even in the absence of 5G, network performance and end user data speeds become limited when a smartphone is frequently handing off between adjacent LTE cells.

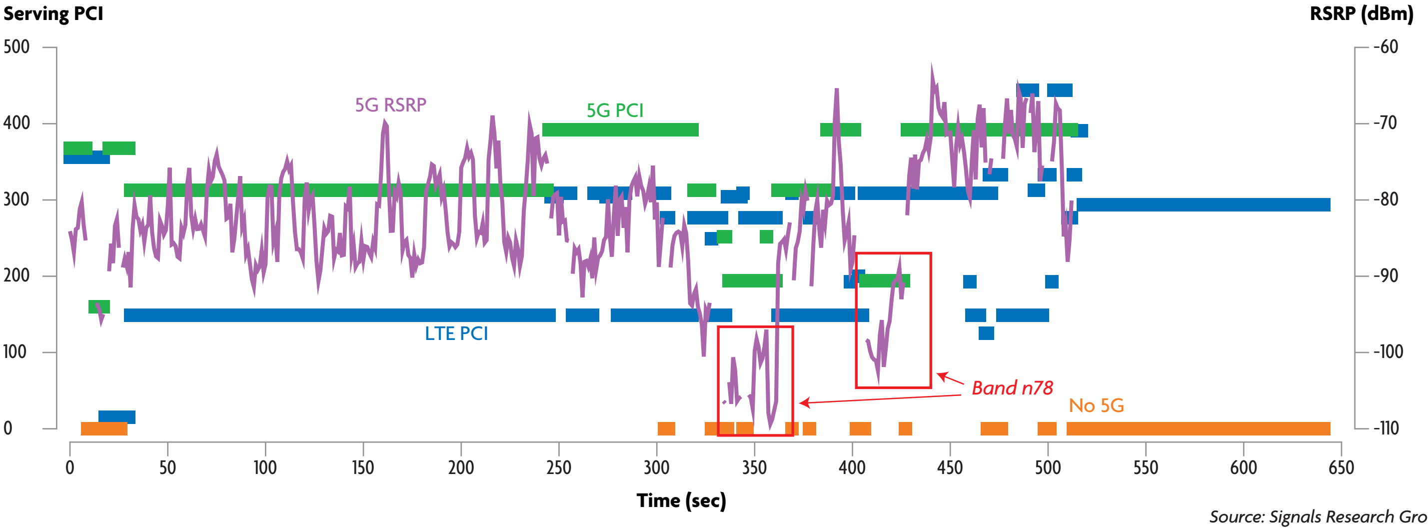
Figure 34. Cell and Handover Count – by technology



Source: Signals Research Group

Figure 35 shows a time series plot of the LTE and 5G PCI values as well as the 5G RSRP, which is plotted along the secondary Y axis. The RSRP includes a mix of mmWave and Band n77, as shown in the figure. It is evident that during the test there were portions of the walk with very few LTE handovers, but there was also a stretch between roughly 300 and 500 seconds when there were frequent LTE handovers. We focus on this area of the test in the next two figures.

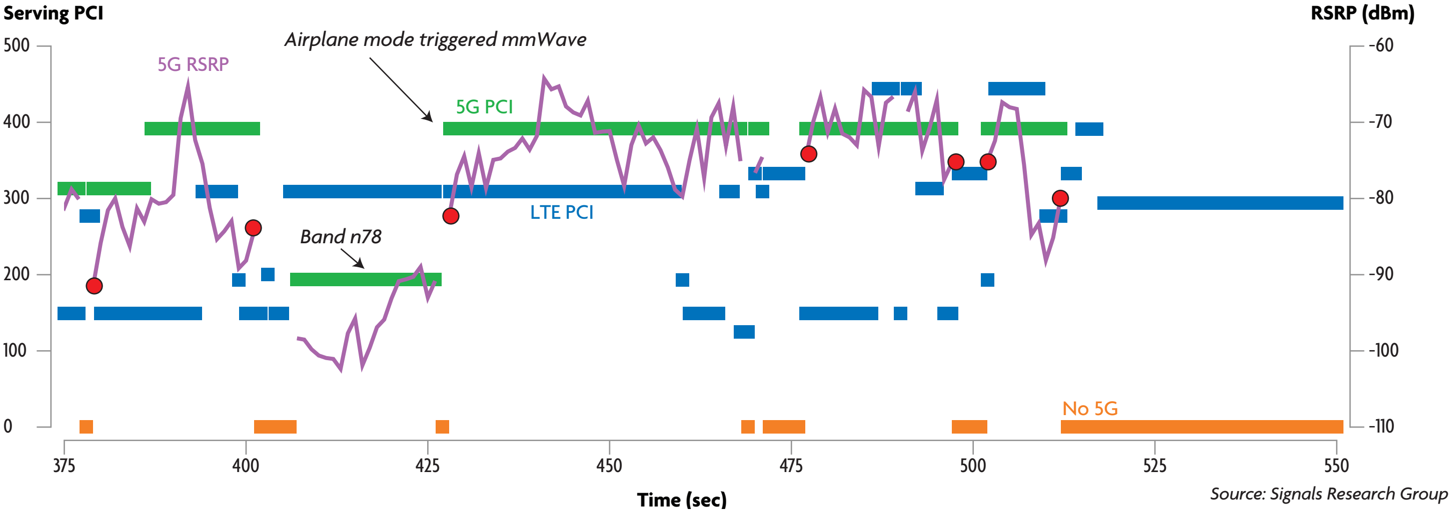
Figure 35. 5G RSRP and PCI Values



Source: Signals Research Group

Figure 36 provides an enhanced view of this portion of the test. We also included red circles highlighting the RSRP values at the start/stop point of the 5G mmWave connection. In each instance, the measured RSRP was more than adequate to establish a reasonably good 5G connection plus the start/stop points occur in conjunction with a change in the LTE PCI. These two observations support our view that 5G mmWave coverage was much better than suggested by other metrics captured during the test. In other words, in the absence of frequent LTE handovers the 5G mmWave connection would have been far more stable and consistent throughout the test. In the figure, we also highlighted one of a few instances when the triggering of airplane mode on the smartphone resulted in the phone reattaching to 5G mmWave.

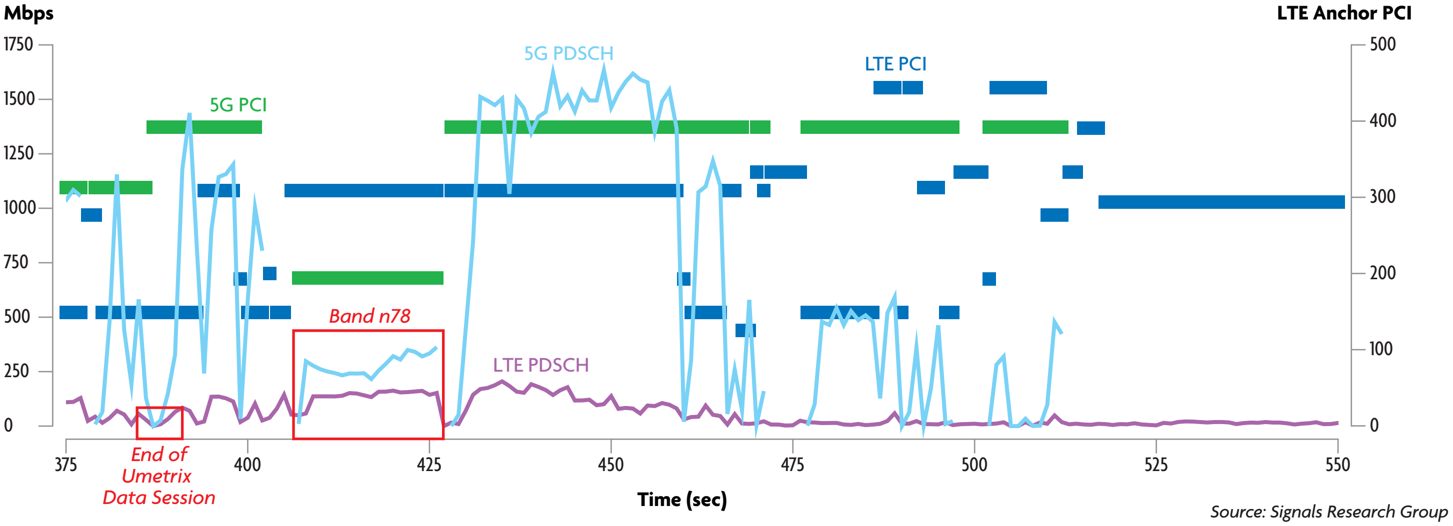
Figure 36. 5G RSRP and PCI Values – time enhanced



Source: Signals Research Group

Finally, Figure 37 provides a time series plot of the LTE and 5G PDSCH throughput along with the LTE anchor cell PCI values, which are plotted along the secondary Y axis. The relative differences in throughput between 5G mmWave and LTE tends to understate the contributions from LTE, but even with this caveat, it is still evident the LTE throughput with the frequent LTE handovers suffered, as did the 5G mmWave throughput.

Figure 37. PDSCH Throughput and LTE PCI Values



Source: Signals Research Group

The other observation from this log file is that each time the smartphone did an LTE handover, the smartphone returned to the LTE RRC connected state instead of retaining the NSA state, as shown in Table 1. In the initial days of 5G mmWave, state transitions took place. In fact, the smartphone even returned to LTE each time it switched SSB beam indices within the same 5G mmWave PCI value. Our expectation based on the testing we've done is that a smartphone should remain in the NSA state when doing handovers involving LTE and/or 5G. Dropping back to LTE has a material impact on total throughput since there can't be any contribution from 5G mmWave if the smartphone is only attached to LTE. In this example, there was an 876 ms gap when the smartphone was not using 5G mmWave.

Table 1. RRC State Information

TIME STAMP	5G mmWave PCI	RSRP	SINR	5G PDSCH Tput	LTE PDSCH Tput	LTE PCI	LTE HO	LTE HO Success	5G HO	5G HO Result	RRC Connected State
2022-04-19 22:08:39.000	392	-78.84	23.65	1367.364	81.07	309					RRC Connected State
2022-04-19 22:08:39.929							Attempt				LTE RRC Connected
2022-04-19 22:08:39.990								Success			LTE RRC Connected
2022-04-19 22:08:40.000	392	-79.72	26.54	19.811	30.242	193					LTE RRC Connected
2022-04-19 22:08:40.306							Attempt				LTE RRC Connected
2022-04-19 22:08:40.352								Success			LTE RRC Connected
2022-04-19 22:08:40.687									Attempt		LTE RRC Connected
2022-04-19 22:08:40.805										Success	NSA RRC Connected
2022-04-19 22:08:41.000	392	-74.95	25.86	303.281	41.541	149					NSA RRC Connected
2022-04-19 22:08:42.000	392	-70.87	23.32	1074.328	43.087	149					NSA RRC Connected
2022-04-19 22:08:43.000	392	-77.31	26.79	1099.94	94.146	149					NSA RRC Connected
2022-04-19 22:08:44.000	392	-69.35	26.74	1216.543	51.87	149					NSA RRC Connected

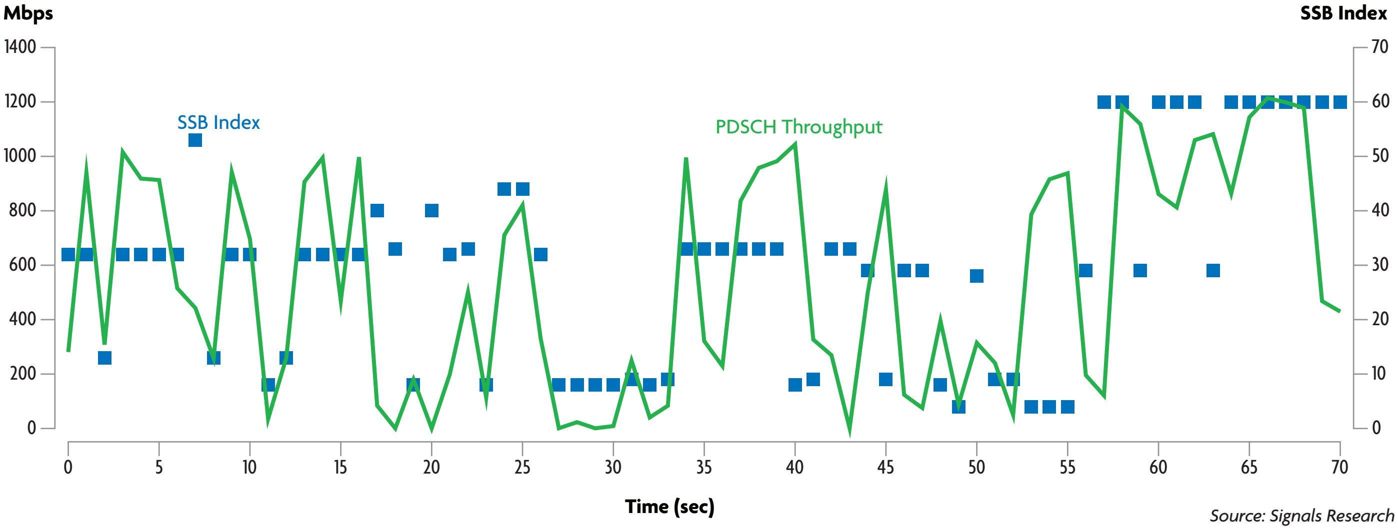
Source: Signals Research Group

The last opportunity for improvement for 5G mmWave performance has to do with beam management. 5G mmWave uses several unique beams to directionally steer the RF energy from the serving 5G mmWave cell site to the mobile devices within its coverage area. It is akin to a laser flashlight versus a lightbulb – the former provides concentrated light over greater distances while the latter just floods an entire region with limited coverage and with RF energy going everywhere, even if it isn't needed.

From our testing, we observed very frequent changes in the SSB beam index being used by the smartphone, even during some stationary tests. We would expect changes in the beam indices while moving through a cell, but the degree to which these changes occurred in our testing in Tokyo was greater than we've seen in other tests that we have done. Further, some of these changes seemed unnecessary, or at least the SSB- SINR and RSRP were good prior to a change in the SSB beam index, plus the change in the beam index didn't necessarily improve either RF metric. The net effect is that when there was a change in a beam index there were several times when there was a hit to the 5G mmWave throughput.

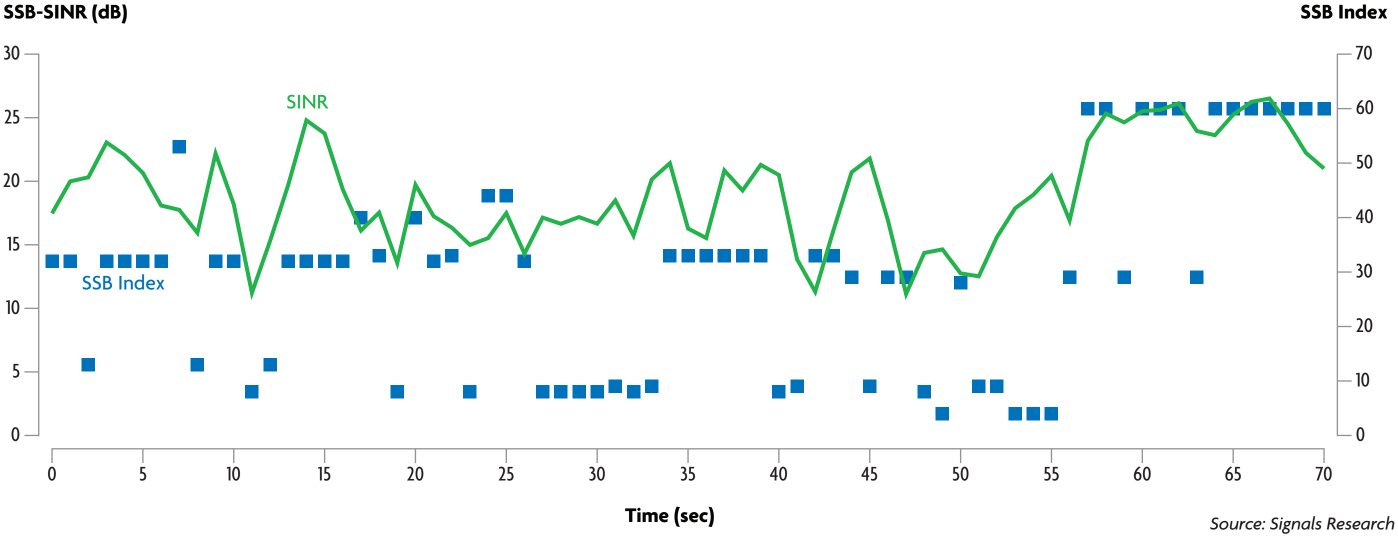
The next three figures show an example of what we just described. Figure 38 provides a plot of the 5G throughput and the SSB beam indices. Figure 39 shows SSB-SINR and the SSB beam indices. Lastly, Figure 40 shows the RSRP and SSB beam indices. Looking at the three figures it is first of all evident that the SSB beam indices changed quite frequently during this walk test. Secondly, while there were instances when a change in the SSB beam index resulted in an improvement in the RF conditions and the throughput, there were also several instances when the change had a negative impact, especially for the PDSCH throughput.

Figure 38. 5G PDSCH Throughput and SSB Beam Indices



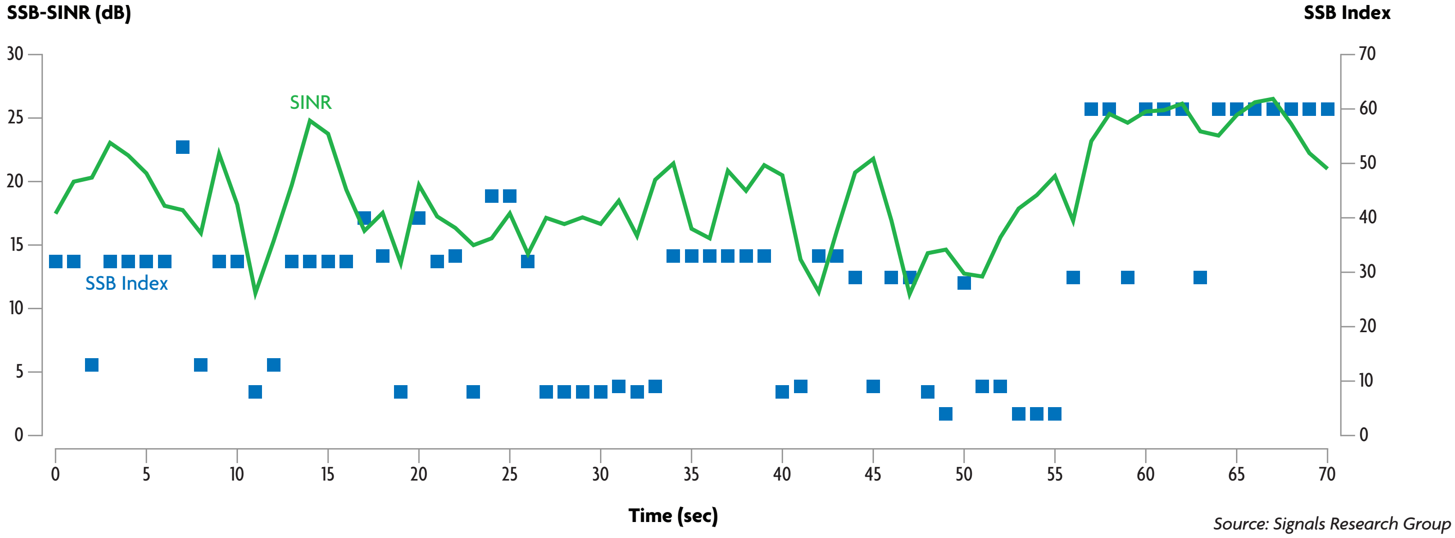
Source: Signals Research Group

Figure 39. SSB-SINR and SSB Beam Indices



Source: Signals Research Group

Figure 40. RSRP and SSB Beam Indices



Source: Signals Research Group

Test Methodology

For these tests we used the Asus smartphone for Snapdragon Insiders with the Snapdragon 888 5G Mobile Platform.

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. For these tests we used the Asus smartphone for Snapdragon Insiders with the Snapdragon 888 5G Mobile Platform.

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

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

We've worked with Accuver Americas since we did our first LTE benchmark study in 2009. For this study, we used the company's XCAL-Solo drive test tool to capture the diagnostic messages from the modem(s) in the smartphone. XCAL-Solo is a handheld unit that makes it relatively easy to walk around a city or stadium while testing and it is an invaluable tool when testing millimeter wave performance. We also used the company's XCAP post-processing software to analyze the chipset logs that we captured.

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

Our collaboration with Spirent Communications goes back to 2006 when we did the industry's first independent benchmark studies of 3G chipsets. For the last several years we have been using the company's Umetrix Data platform to generate high bandwidth data transfers during our tests. For the testing done in this study, we used a Umetrix data server located in Japan and outside of all operators' networks to ensure maximum performance. The server, with 10 Gbps backhaul, supports HTTPS, HTTP and UDP protocols, supporting downlink, uplink, or simultaneous downlink/uplink data transfers.

We binned the logged chipset data into one-second time increments, thus making it more manageable to analyze the data. Since network parameters are literally reported at the millisecond level and they are constantly changing, even when standing at a fixed location, a single measurement point in a log file can be based on nearly 1,000 samples.

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