December 16, 2022

SiGNALS Flash!

Dispatches from the frontier of wireless

IN THE SPIRIT OF GIVING: SAMPLE RESULTS AND ANALYSIS OF A COMMERCIAL IMPLEMENTATION OF 8-LAYER 5G MU-MIMO

SiGNALS Research Group
www.signalsresearch.com

EXECUTIVE SUMMARY

Signals Research Group (SRG) just completed the industry's first independent benchmark study of 5G MU-MIMO (Multi-User MIMO) in a commercial network while using a mix of commercial and precommercial devices. In the spirit of giving, we are sharing some sample results and analysis from that testing, which occurred during the week of December 5th on the T-Mobile network in southern California. Given the amount of information provided in a free report, one can rightly conclude that we have a wealth of data that we will be releasing in a forthcoming *Signals Ahead* report that will be exclusively available to our subscribers. The target publication date is the week of January 9th.

T-Mobile provided logistical support and access to its network, but consistent with all *Signals Ahead* studies, there was no outside sponsorship. These studies are entirely funded by our loyal Signals Ahead subscribers. Ericsson is aware that we did the testing, but they have no insight into the results or the contents of this Signals Flash! We plan to discuss the results with both companies just prior to publishing the report since we have some important questions with hoped-for answers that will feed into our observations.

The results in this *Signals Flash!* stem from some preliminary testing that we did onsite at the T-Mobile facilities in Irvine, CA before venturing out into the field. The MU-MIMO performance discussed in this report is not necessarily reflective of overall MU-MIMO results. On the one hand the RF conditions were ideal (SINR = ~30 dB) while on the other hand, the placement of the four smartphones and their location relative to the serving cell would lead many people to conclude that MU-MIMO wasn't even possible from this location. Read on! As always, unlike our subscription-based *Signals Ahead* reports, you may forward this *Signals Flash!* report to whomever you want.

- **Our Thanks.** Our study would not have been possible without the continued support of Accuver Americas and Spirent Communications. We used XCAL5 from Accuver Americas to log the chipset diagnostic messages and the company's XCAP post-processing software to analyze the data. We used Umetrix Data from Spirent Communications to provide continuous high bit rate UDP/HTTP data streams to load the network. We've worked with both companies for nearly 15 years and their invaluable support is critical to our ability to do these types of studies.
- **The Devices.** We used commercially available OnePlus 10 Pro and Samsung Galaxy S22 smartphones (both Qualcomm chipsets) as well as a soon-to-be released Arcadyan fixed wireless CPE with a MediaTek 5G chipset. The results in this Flash! stem from using 3 OnePlus 10 Pro smartphones and 1 Galaxy S22 smartphone.
- **8 Layers Achieved.** Thanks to SRS-based MU-MIMO, we frequently achieved simultaneous pairing across all four phones, resulting in a 76% increase in the MIMO layer count/RB usage relative to what is possible with 4x4 SU-MIMO. We explain.
- **Throughput and Spectral Efficiency.** Total average throughput on the Band n41 100 MHz P Cell was 2.4 Gbps, or 82% higher than what we observed with a single UE doing 4x4 SU-MIMO. Doing the math, the downlink spectral efficiency was a very impressive 29.6 bps/Hz.
- **Stay Tuned.** We previously wrote that MU-MIMO can be a game changer for fixed wireless access. We haven't yet analyzed other test results, but we collected the data, and we observed the impact of disabling MU-MIMO/SRS in the network. Suffice it to say, we're on track to confirming our hypothesis.


COMING SOON!
5G: The Greatest Show on Earth!
MU-MIMO AND THE TOWER OF POWER
CHAPTER 1: THE 8-LAYER CONFRONTATION
PART OF "THE MOTHER OF ALL NETWORK BENCHMARK TESTS" SERIES OF REPORTS

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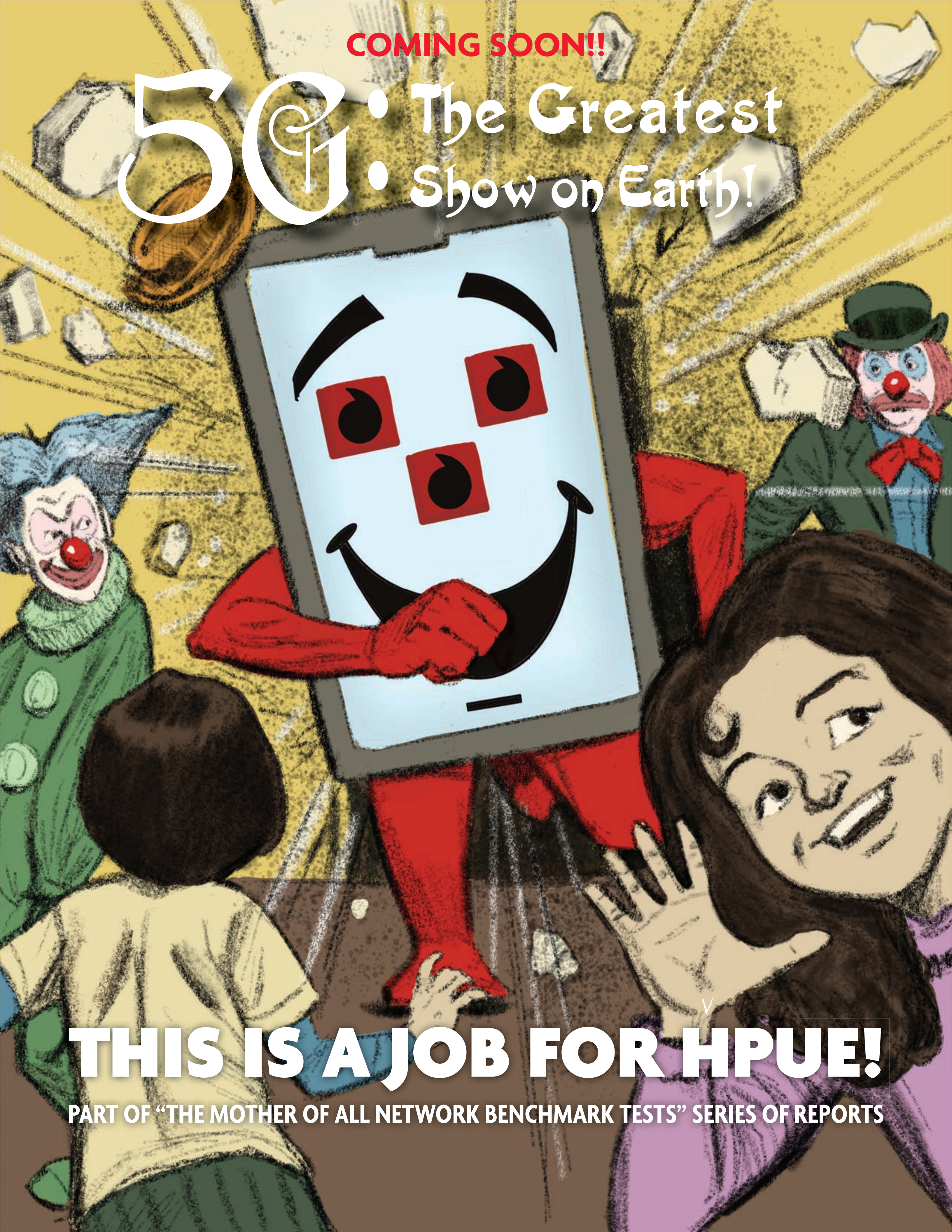
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PART OF “THE MOTHER OF ALL NETWORK BENCHMARK TESTS” SERIES OF REPORTS

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This Signals Flash! contains some background information, a primer on MU-MIMO, the results and analysis from a preliminary test we conducted in a commercial network, and our test methodology.

BACKGROUND

Over the years we have done multiple MIMO-related studies and they always prove to be quite popular. From our perspective, they are also the most interesting studies to conduct since we frequently uncover the unexpected. In fact, we got so distracted writing this report that we missed the first half of France versus Morocco. Sacre blue! They are also quite differentiated since we've done these studies early in the game, or prior to many operators deploying the MIMO feature we tested, while we've done a few things that seldom get done. It isn't every day you get a mobile operator, let alone two mobile operators, to disable MIMO in its network so that you can do comparative testing. We pulled off that feat with 2x2 MIMO testing back in the good old days of LTE.

We tested 5G MU-MIMO in the past and we published a *Signals Flash!* report stemming from that study (SF 09/09/20, "Sweet 16"). That particular study, which looked at a precommercial implementation of 16-layer MU-MIMO, was done for a client but we were able to share some results with an external audience. One other MU-MIMO-related study involved Sprint's LTE Band 41 network back in November 2018 (SA 11/29/18, "The Matrix"). We've also tested 2x2 SU-MIMO (SA 08/12/13, "Fifty Shades of MIMO"), 4x2 SU MIMO (SA 07/08/14, "By the Light of the Silvery Moon") and 4x4 SU-MIMO (SA 01/09/17, "Finding MIMO"). As long as we can keep coming up with clever report titles, we plan to keep benchmarking MIMO.

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We've had 5G MU-MIMO on our bucket list for at least a year, but the industry wasn't ready until now to proverbially drop its drawers and submit to a full rectal exam. When doing our FR1 device/chipset benchmark study (SA 12/07/22, "FR1 in the Wild") we encountered MU-MIMO in the Verizon Band n77 network in Minneapolis, and upon questioning, Verizon confirmed it was evaluating the technology.

The industry wasn't ready until now to proverbially drop its drawers and submit to a full rectal exam and submit to a full rectal exam.

We subsequently coordinated with T-Mobile to test 8-layer MU-MIMO in its network in southern California where Ericsson is the infrastructure supplier. Although the operator hasn't widely deployed the feature, it did enable MU-MIMO in a large swath of sites with 10 Gbps backhaul that provided us with a great playground to do our tests. In addition to a few initial tests at the T-Mobile facility with the radios located on the roof of the building, we did fairly extensive testing at several sites in Buena Park and Irvine, CA. We have yet to analyze that data, but we know from merely collecting the data that we observed strong gains from the presence of MU-MIMO in the network. We will be publishing the results of that study in January 2023.


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5G: The Greatest Show on Earth!
GROUP 2
Galaxy S20 5G
Galaxy S22 5G
Pixel 6a
iPhone 13 mini
Motorola edge (2022)
VOLUME 29: CAGE MATCH
(FR1 IN THE WILD!)

MU-MIMO, CSI-RS AND SRS (COPIED AND EDITED FROM AN EARLIER SIGNALS FLASH!)

There are distinct differences between Massive MIMO and MU-MIMO, just as there are distinct differences between SU-MIMO (Single-User MIMO) and MU-MIMO (Multi-User MIMO). Taking it one step further, there are different variants of MU-MIMO and SU-MIMO, including CSI-RS and SRS implementations. Massive MIMO and MU-MIMO are not unique to 5G NR. In fact, we've tested them when we did a benchmark study of Sprint's LTE Band 41 network back in November 2018.

SU-MIMO and MU-MIMO are similar in that with certain radio conditions they can reuse/duplicate network resources, specifically Physical Resource Blocks (PRB), to increase data speeds and/or sector throughput. With SU-MIMO, the network scheduler can simultaneously assign the same network resource, or Resource Block (RB), to serve a single mobile device. 2x2 SU-MIMO can reuse the same RB twice to effectively double the data speed and 4x4 SU-MIMO can reuse the same RB four times to quadruple the data speed. The exact gains are never a doubling or a quadrupling since some inefficiencies get introduced while the requisite pristine conditions are rarely achieved.

SU-MIMO directly benefits consumers by increasing their data speeds, meaning it indirectly increases overall throughput and spectral efficiency.

2x2 SU-MIMO has been around since the days of HSPA+ while 4x4 MIMO never gained market traction until LTE. 4x4 MIMO was included in the first LTE release (Release 8) but vendors didn't fully support it and operators didn't deploy it until several years later. SU-MIMO directly benefits consumers by increasing their data speeds, meaning it indirectly increases overall throughput and spectral efficiency. In MIMO vernacular, each unique data stream is called a layer, meaning 4x4 SU-MIMO supports up to four layers, all serving a single mobile device.

MU-MIMO is conceptually like SU-MIMO in that it can reuse network resources when certain channel conditions are satisfied. It differs in that the total number of layers is higher than what is possible with SU-MIMO and the layers can be shared between multiple mobile devices, assuming they meet certain algorithmic parameters.

With CSI-RS (Channel Status Information – Reference Signal), the gNB sends a signal to the mobile device, the mobile device receives the signal and estimates the channel quality, at which point it reports this information back to the gNB. With this information, the gNB determines how to weight the transmitted beams back to the mobile device. To keep things manageable, the gNB selects the weighting factors from a codebook, which defines predetermined weighting factors based on the CSI-RS information. The tradeoff is that the codebook limits the number of possible weighting factors so the scheduler may not be able to select the optimal weighting factors for each beam.

The MU-MIMO implementation we tested in the T-Mobile network used a flavor of MU-MIMO which leverages SRS (Sounding Reference Signal). The network also supported codebook-based MU-MIMO, but the real benefits of MU-MIMO come from SRS. With SRS, the mobile device transmits a signal to the gNB, similar to a reference beacon, which the gNB uses to determine the channel quality. The gNB can, for example, determine if it can easily distinguish one mobile device from another mobile device in the network, and if the signal quality is good enough, it enables MU-MIMO between the two devices. The more devices in the network that the gNB scheduler can uniquely identify translates into more pairing of mobile devices in the network. The word "pairing" is commonly used to refer to mobile devices that are sharing the same network resources.

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MU-MIMO is limited, at least for now, to the primary cell (P Cell). Therefore, the results in this report include a mix of MU-MIMO (P Cell) as well as contributions from the secondary cell(s), or S Cell. The phones and CPEs, not to mention the network, supported the standalone (SA) network architecture so there wasn't any contribution from LTE.

SAMPLE RESULTS AND ANALYSIS

As indicated previously, the test result in this Signals Flash! stems from some initial testing we did at the T-Mobile facility in Irvine, California using a commercial cell site. The RF conditions were ideal with SINR = ~30 dB on the four phones. Conversely, we did the testing in a small first floor office with the four smartphones placed in a haphazard manner – wherever we could find space – without any attempt on our part to optimize the pairing. The 5G radio site was located on the roof of a two story building, almost directly over our heads when doing the tests. Figure 1 shows a picture of the four phones when doing this test as well as a picture of the outdoor cell site. For this test we used three OnePlus 10 Pro smartphones and one Galaxy S22 smartphone.

Figure 1. MU-MIMO Test Environment

Source: Signals Research Group

IN CASE YOU MISSED IT:
SIGNALS AHEAD BACK ISSUES

- **12/7/22 "5G: The Greatest Show on Earth! Vol 29: Cage Match (FR1 in the Wild!)"** SRG just completed its 29th 5G benchmark study. For this endeavor we collaborated with Accuver Americas and Spirent Communications to conduct an independent benchmark study of several 5G smartphones operating in mid-band 5G spectrum and representing chipsets from MediaTek, Qualcomm, and Samsung.

  Highlights of the Report include the following:

  Our Thanks. We did this study in collaboration with Accuver Americas (XCAL-M, XCAL-Solo and XCAP) and Spirent Communications (Umetrix Data). SRG is responsible for the data collection and all analysis and commentary provided in this report.

  Our Methodology. Testing took place on the T-Mobile network (Band n41) in the suburbs of Minneapolis-Saint Paul, MN. The network is comprised of 140 MHz of Band n41 spectrum (100 MHz + 40 MHz) as well as 5G in Band n71 and the requisite LTE spectrum - primarily Band 66 and Band 2 serving as the anchor cell. We tested the smartphones in pairs with the Galaxy S22 serving as the reference smartphone used to evaluate performance of the other smartphones in the mix.

  The Scope. We used the Galaxy S22, Galaxy S20 Ultra, iPhone 13, Google PIxel 6a, Galaxy A13, and Motorola edge (2022) smartphones. These smartphones represent 5G chipsets from MediaTek, Qualcomm and Samsung. GIven some limitations in logging detailed chipset data, we included a mix of physical layer and application layer results in our analysis

  A New Sheriff in Town. Based on our analysis of the results, we declare the iPhone 13 as the ""unofficial"" top performing 5G smartphone of the group. We include the ""unofficial"" disclaimer because our analysis was limited to application layer throughput with this phone since we weren't able to log chipset data. Given the network pushed most of the traffic to Band n41 on the S22, we assume it behaved the same way with the iPhone, meaning potential differences in LTE performance between the two phones wouldn't explain the overall results we observed.

  LTE is becoming less relevant on the T-Mobile network. In addition to 5G Band n41 carrying the super-majority of the total traffic, the 5G network is quickly moving to the standalone (SA) network architecture as the default architecture, even with Band n41. This situation means LTE is becoming inconsequential, especially for those smartphones that support SA mode in Band n41.

- **10/31/22 "5G: The Greatest Show on Earth! Vol 28: Cage Match (FR2 in the Wild!)"** SRG just completed its 28th 5G benchmark study. For this endeavor we collaborated with Accuver Americas and Spirent Communications to conduct an independent benchmark study of several 5G mmWave smartphones with chipsets from MediaTek, Qualcomm, and Samsung.

  Highlights of the Report include the following:

  Our Thanks. We did this study in collaboration with Accuver Americas (XCAL-M, XCAL-Solo and XCAP) and Spirent Communications (Umetrix Data). SRG is responsible for the data collection and all analysis and commentary provided in this report.

  Our Methodology. Testing took place on the Verizon Wireless network in downtown Minneapolis. The network is comprised of 400 MHz in the downlink and 200 MHz in the uplink. We did walk testing with individual phones and two phones in tandem, using the Galaxy S22 Ultra as the comparative model. We also looked at current efficiency or the amount of current required to deliver the achieved throughput. These tests occurred while stationary. We also included current efficiency tests using LTE, Wi-Fi and mid-band 5G for comparison purposes.

  The Scope. We used the Galaxy S22, Galaxy S22 Ultra, Google PIxel and Motorola edge (2022) smartphones, as well as the Galaxy S20 UW as a legacy smartphone for comparison purposes. These smartphones represent 5G chipsets from MediaTek, Qualcomm and Samsung. GIven some limitations in logging detailed chipset data, we included a mix of physical layer and application layer results in our analysis

  Significant Gains since 2019. We documented a 180% gain in current efficiency relative to testing we did back in 2019 using the Galaxy S10 smartphone. The gains were due to a mix of higher throughput and lower current drain. Further, today's mmWave networks now support up to 800 MHz in the downlink and 200 MHz in the uplink (the latter supported by all phones we tested), while previously the uplink data went over LTE.

  Price Does Not Equal Performance. More expensive smartphones do not necessarily deliver better performance with the entry-level/mid-tier Motorola edge (2022) more than holding its own against the Galaxy S22 Ultra. However, the Google Pixel 6a lagged its peers in all categories.

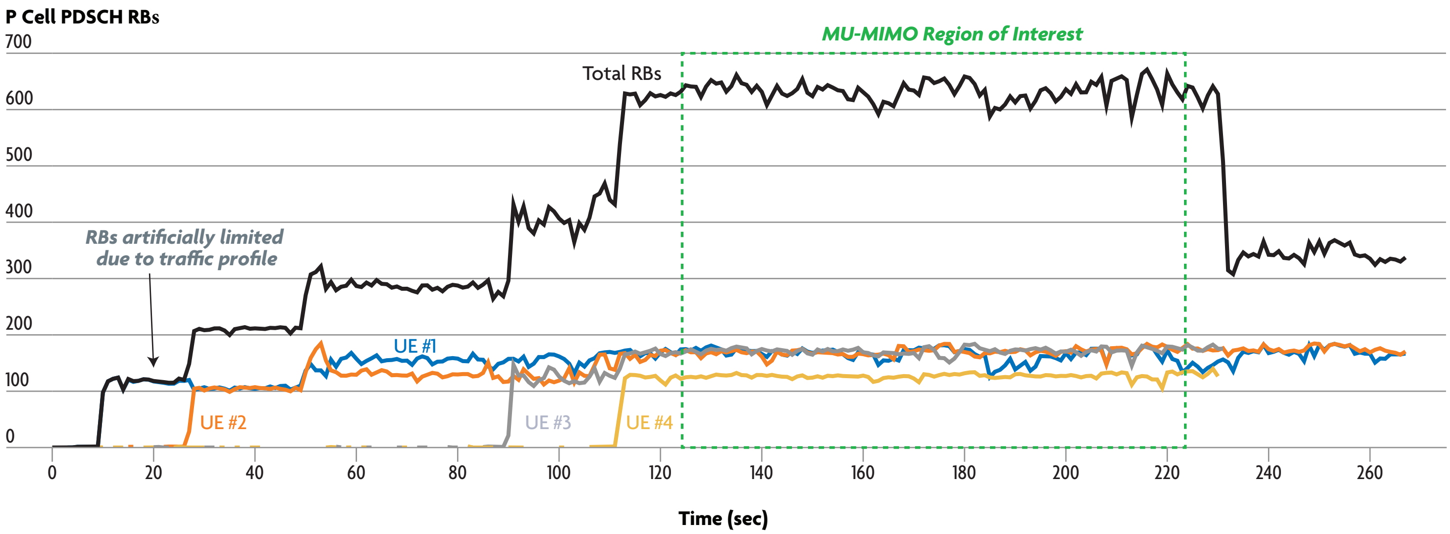
  Current Efficiency is Nuanced. Although Wi-Fi can and should achieve better current efficiency than 5G mmWave, this outcome didn't always occur. Much depends on the ISP/service plan associated with the Wi-Fi AP. Not everyone has access to a 1 Gbps connection, especially at public venues.

We used Umetrix Data to push UDP data streams to the smartphones. For this test we used a 750 Mbps profile since we felt the combined theoretical maximum throughput from 4 smartphones (4x750 = 3,000 Mbps) would be sufficient. In hindsight, and for reasons discussed in a bit, we should have used a slightly higher data stream.

Figure 2 provides a time series plot of the PDSCH resource block (PRB) allocations for the four smartphones. For those readers familiar with logging tools, we used the "RB incl 0" KPI since this parameter inherently includes the impact of unscheduled time slots/RBs when the smartphone isn't allocated any network resources. As shown in the figure, the total number of RBs in the sector continued to increase with the introduction of each smartphone – we time sequenced the start of the data transfers to make the impact of MU-MIMO more visual.

We used the period between 125 seconds and 225 seconds for all of our MU-MIMO analysis. Since the network leveraged the S1 Cell (Secondary 1 Cell) to send some of each 750 Mbps data stream to the respective phone, the number of scheduled RBs on the P Cell was initially limited, as shown in the figure. In other words, the number of total RBs used by UE #1 was below the maximum possible for a single UE. Further, although the figure implies UE #4 didn't pair as well as the other four phones, the reality is this phone (the S22) was using two secondary cells (40 MHz TDD of Band n41 and 20 MHz FDD of Band n25), so it didn't need to receive as much data over the P Cell with MU-MIMO. Although we don't know for certain, it is likely if we had disabled the secondary cells on the four phones (or increased the UDP throughput), the total number of scheduled RBs during the highlighted period would be higher than shown in the figure.

Figure 2. Band n41 P Cell Resource Block Allocations Time Series – by UE



Source: Signals Research Group

Figure 3 provides the RB pairing efficiency associated with each smartphone as well as the overall pairing efficiency. The percentages are relative to the maximum number of available RBs that can be scheduled to a single smartphone. With MU-MIMO, although each smartphone's RB allocation was below what was possible with a single smartphone in the network, the total RBs across the four phones was more than three times higher than possible with a single smartphone.

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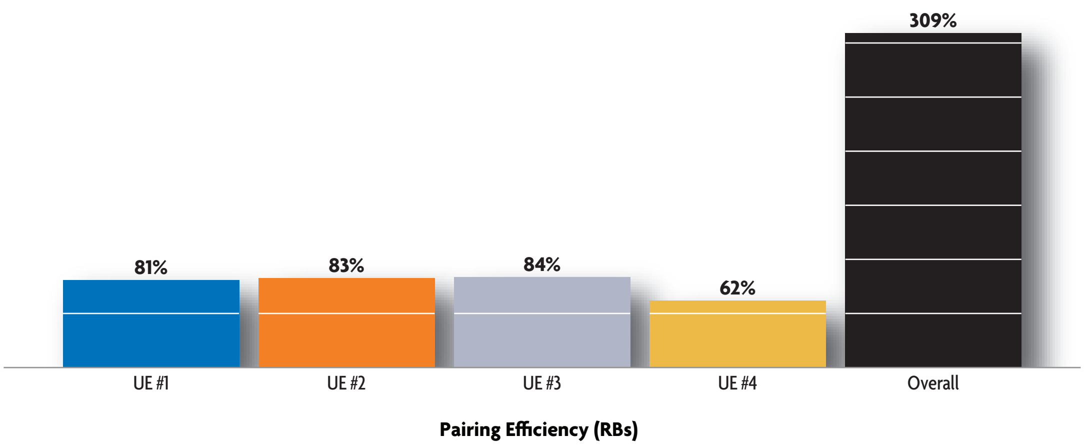
Figure 3. Band n41 P Cell Resource Block Pairing Efficiencies – by UE



Source: Signals Research Group

From our perspective, reusing the same RB is only efficient if the number of MIMO layers is maintained. For example, if the four pairing phones were only using a single layer, then there wouldn't be any benefit associated with using MU-MIMO. Figure 4 shows the number of P Cell MIMO layers for each smartphone, but with a slight twist. We adjusted the reported number of MIMO layers to take into consideration the scheduling of resource blocks.

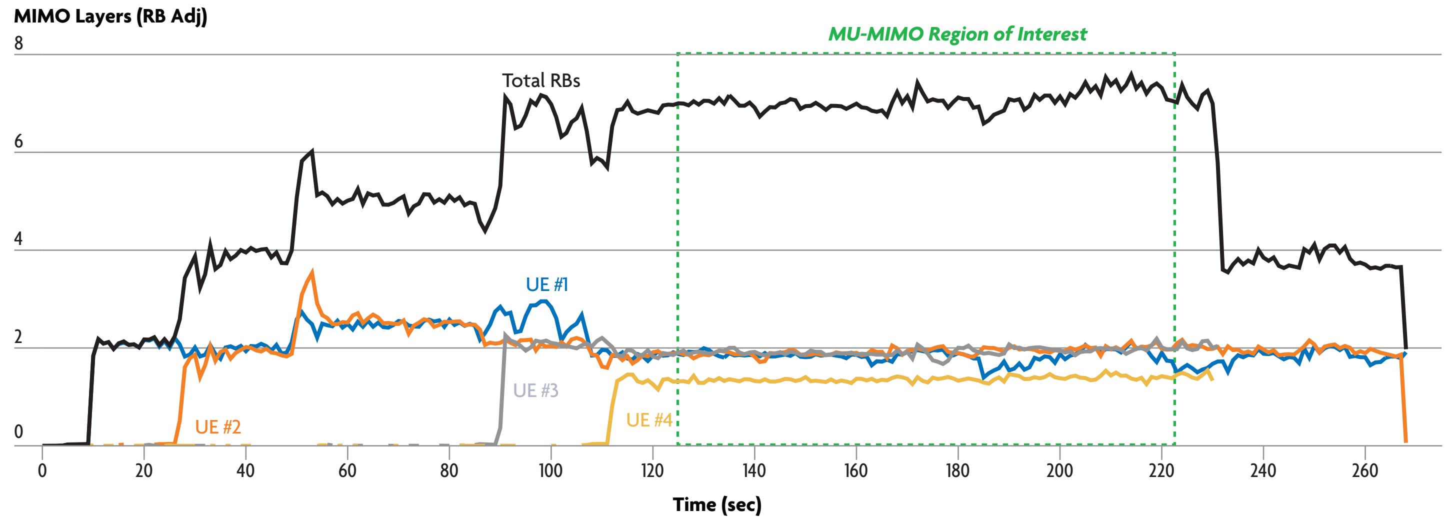
Reusing the same RB is only efficient if the number of MIMO layers is maintained.

With SU-MIMO, an RB is going to a single smartphone, so it is straightforward to directly associate the layer count with a smartphone. However, if some RBs are shared then it is a bit more convoluted. Therefore, for each reported layer count (binned in one second increments), we weighted the reported layer count by the percentage of scheduled RBs (binned in one second increments) relative to the maximum available RBs. For example, if the reported layer count was Rank 2 and the RB incl 0 value indicated 100% pairing, then the actual MIMO layer count would also be Rank 2. Any inefficiencies in the MIMO pairing would reduce the layer count from what gets reported by the logging tool.

We weighted the reported layer count by the percentage of scheduled RBs relative to the maximum available RBs.

Although we don't show the figure in this report, we also looked at slot utilization. During the MU-MIMO period of interest UE #1 through UE #3 had a downlink slot utilization efficiency of approximately 95% while UE #4 had an efficiency in the range of 75-80%.

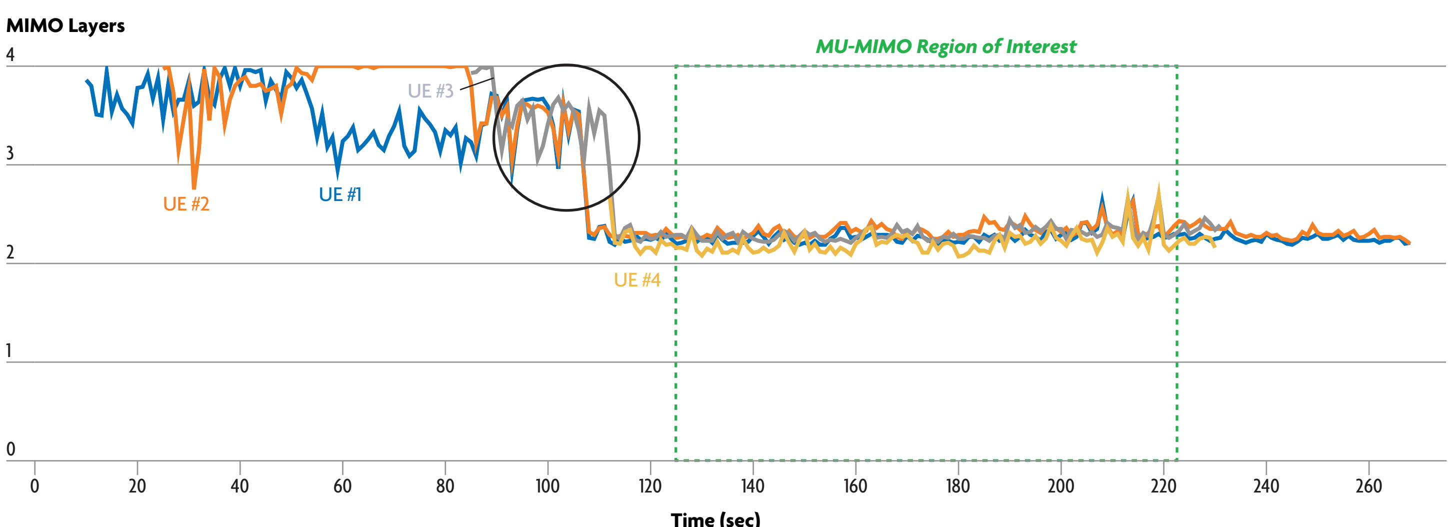
Figure 4. Band n41 P Cell MIMO Layers (RB Adj) Time Series – by UE



Source: Signals Research Group

Figure 5 shows what would happen if we didn't make this adjustment. Although the MU-MIMO region of interest between 125 and 225 seconds shows the phenomenon, it is more apparent in the circled region. Looking at these results, one could conclude the total layer count was well above the theoretical limit of 8 layers, which obviously was not the case. By making the aforementioned adjustments, we obtain results that are accurate and consistent with the 8 layer limitation.

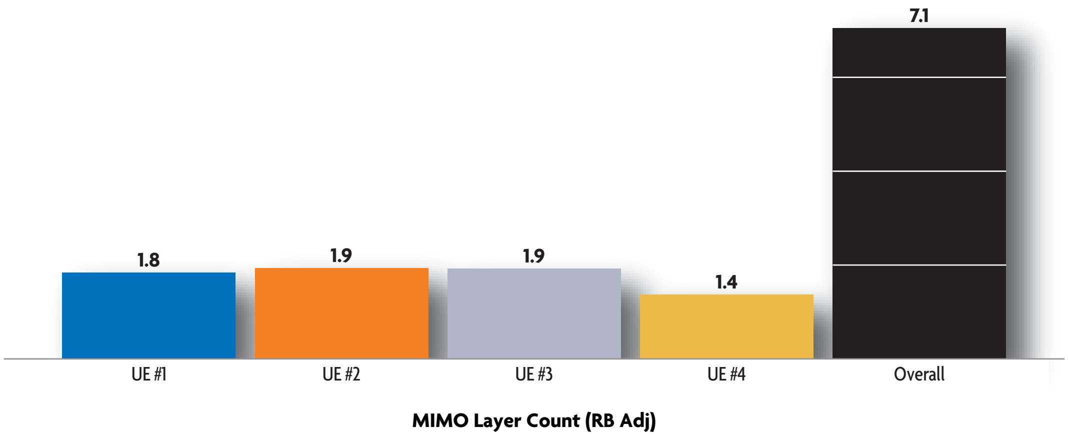
Figure 5. Band n41 P Cell MIMO Layers Time Series – by UE



Source: Signals Research Group

Figure 6 shows the average number of MIMO layers used by each smartphone, once again adjusted for MU-MIMO pairing efficiency. The figure suggests each phone's average number of MIMO layers was below 2 layers, but the correct interpretation of the information is the phones consistently used MIMO Rank 2, with the inefficiency (Layer Count < 2) due to the scheduling of RBs.

Figure 6. Band n41 P Cell Average MIMO Layers (RB Adj) – by UE



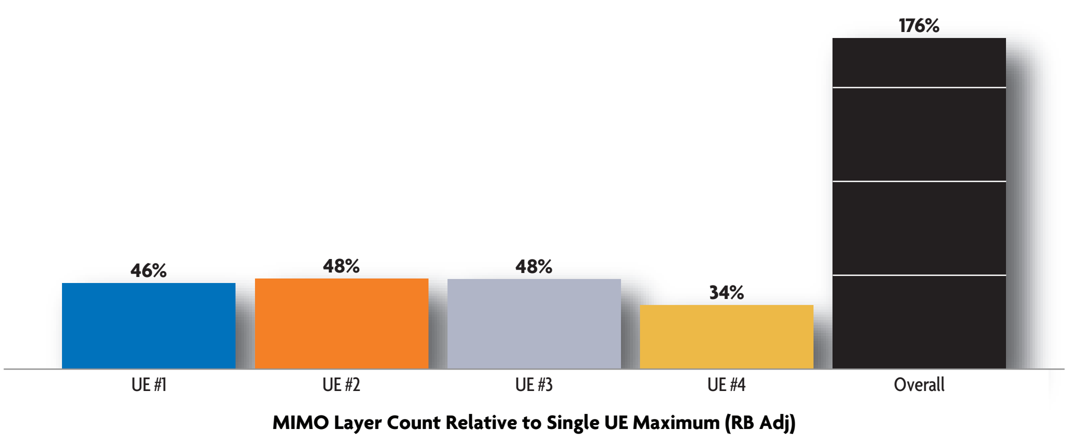
Source: Signals Research Group

Looking at Figure 7, which stems from information provided in the previous figure, we conclude that MU-MIMO pairing (8 phones pairing with MIMO Rank 2) was 76% efficient – 100% efficiency would mean all four smartphones always received all RBs and always received two MIMO data streams. In this figure, we assumed the maximum number of MIMO layers for a single UE was 4 layers, hence a smartphone using just 2 layers would be 50% of the maximum UE capability.

We point out the network also supported 8-layer MU-MIMO pairing with two smartphones, each supporting 4 layers, as well as MU-MIMO pairing with eight smartphones, each supporting 1 layer. We tested the former but not the latter. We'll include the former in the upcoming Signals Ahead report, plus Figure 16 in the Test Methodology chapter shows some KPIs from one smartphone when paired with a second smartphone. No other phones in our possession were attached at the time, but we can't rule out other phones in the commercial network.

The network also supported 8-layer MU-MIMO pairing with two smartphones, each supporting 4 layers, as well as MU-MIMO pairing with eight

Figure 7. Band n41 P Cell Relative MIMO Layers to Maximum Possible (RB Adj) – by UE

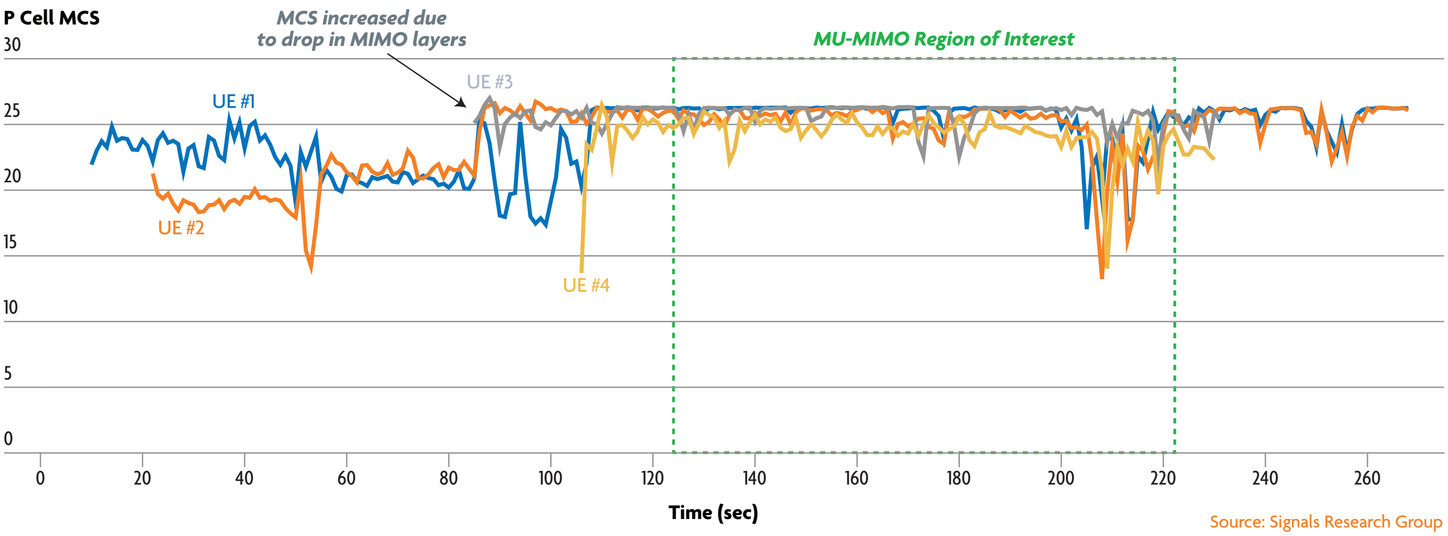


Source: Signals Research Group

Although perhaps a bit less interesting, Figure 8 and Figure 9 share insight on the allocation of MCS (Modulation and Coding Scheme). It is one thing to pair smartphones with RBs and layers. It is another thing to achieve this outcome without impacting the MCS value. In this test, this outcome was generally achieved although there were some noticeable fluctuations just after 200 seconds into the test. We may have repositioned a smartphone during this time and the sudden movement, combined with the close placement of the four smartphones to each other could have had an impact. Interestingly, the MIMO layers (without RB adjustments) shown in Figure 5 show an uptick in the number of layers during this time, implying the smartphones were not pairing as efficiently.

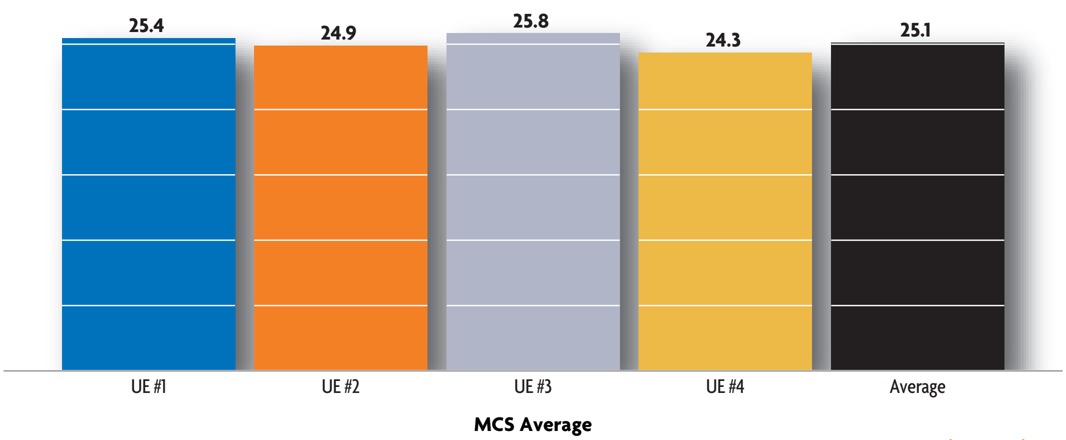
It is one thing to pair smartphones with RBs and layers; it is another thing to achieve this outcome without impacting the MCS value.

Figure 8. Band n41 P Cell MCS Allocations Time Series – by UE



Source: Signals Research Group

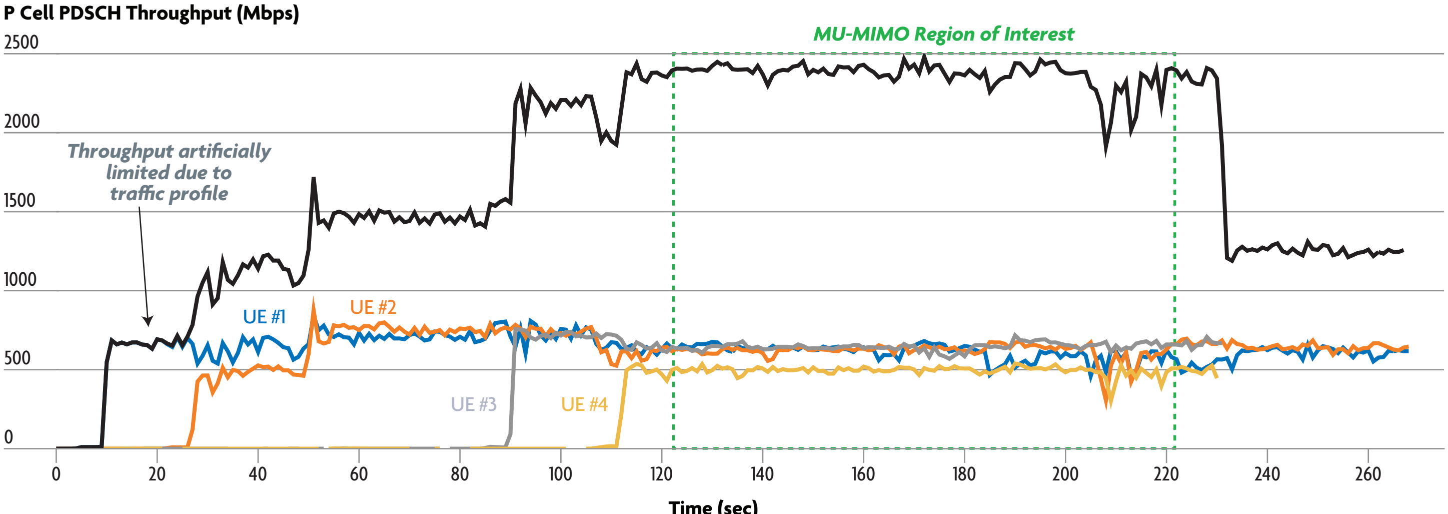
Figure 9. Band n41 P Cell Average MCS Allocations – by UE



Source: Signals Research Group

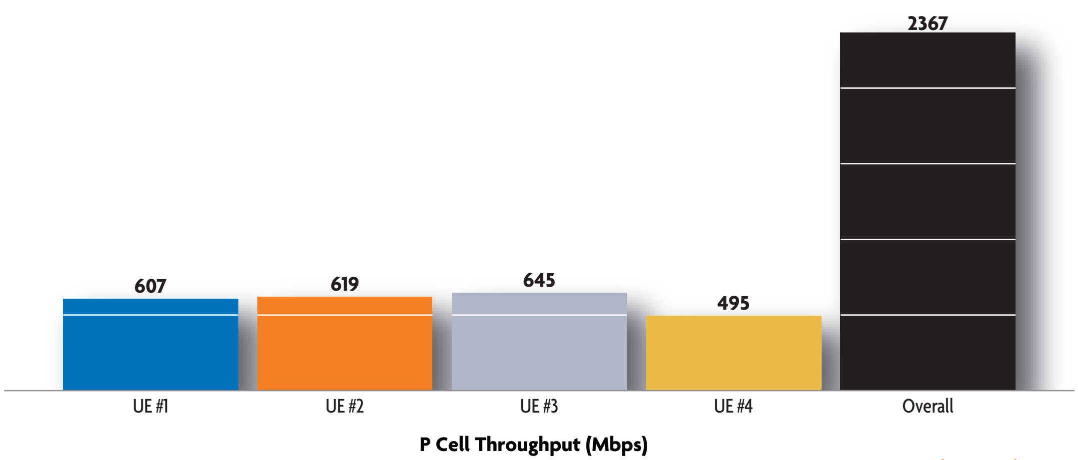
For readers that care only about throughput, we have figures just for you. Figure 10 provides a time series plot of the 5G P Cell PDSCH throughput, or the throughput of each smartphone on the 5G radio channel which supported MU-MIMO. Once again, the lower throughput toward the beginning of the test was an artifact of the 750 Mbps Umetrix Data profile that we selected, combined with the smartphone using 2CA. However, with all four smartphones receiving 750 Mbps of application layer throughput, we came close to maximizing the performance of MU-MIMO in the 100 MHz radio channel. The average P Cell PDSCH throughput during this time was nearly 2.4 Gbps, as shown in Figure 11.

Figure 10. Band n41 P Cell PDSCH Throughput Time Series – by UE



Source: Signals Research Group

Figure 11. Band n41 P Cell Average PDSCH Throughput – by UE

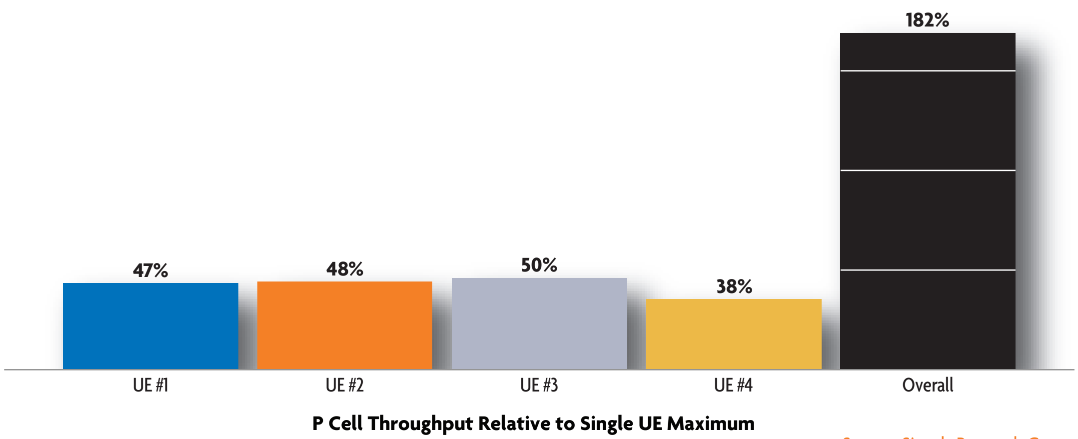


Source: Signals Research Group

Slicing this information slightly differently, Figure 12 shows that the total sector throughput was 82% higher than possible with a single smartphone from the same location using 4x4 MIMO. Although it isn't shown in this report, we observed an average single UE throughput of 1,300 Mbps in a different test from this location. Since each smartphone's throughput was below this threshold, each smartphone's individual performance suggests inefficiencies relative to what is possible with a single smartphone. However, without 8-layer MU-MIMO, the reality is each smartphone's potential throughput would likely be limited to only approximately 325 Mbps (one-fourth of 1,300 Mbps).

The total sector throughput was 82% higher than possible with a single smartphone from the same location using 4x4 MIMO.

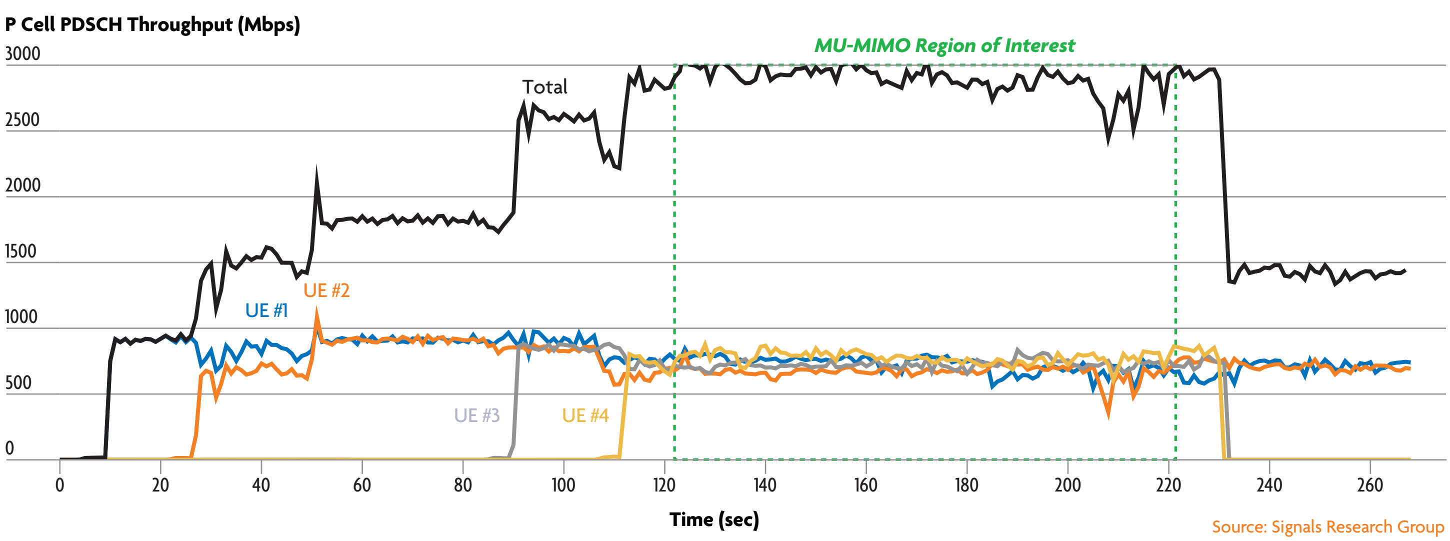
Figure 12. Band n41 P Cell PDSCH Throughput Relative to Maximum Possible Throughput – by UE



Source: Signals Research Group

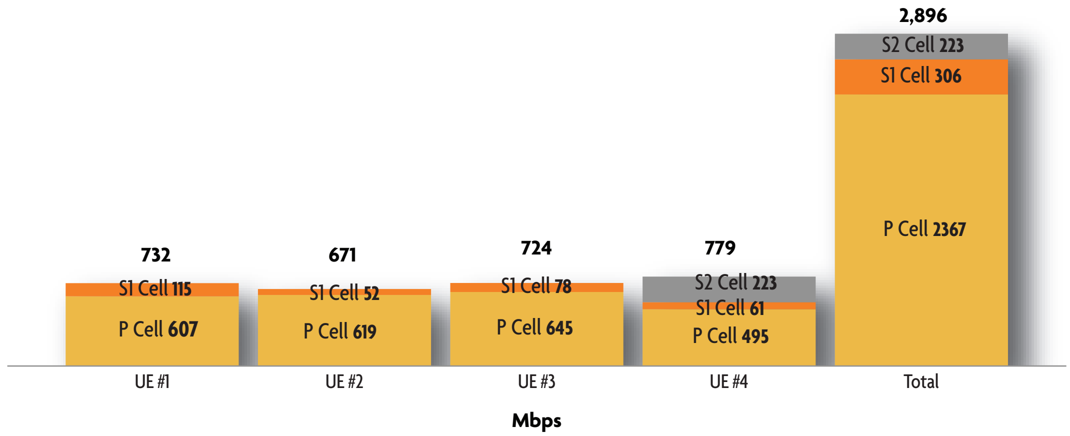
Although MU-MIMO functionality only occurred in the 100 MHz P Cell, it is useful to look at the overall performance in the sector. Figure 13 provides a time series plot of the 5G PDSCH throughput. Each smartphone's throughput includes the P Cell and one or more secondary cells. Figure 14 provides the distribution of throughput for each smartphone between the component carriers. In the case of the Galaxy S22 (UE #4), its throughput included 223 Mbps from Band n25. The information in this figure is the primary reason why we believe its MU-MIMO pairing efficiency was lower than the other three smartphones. The Galaxy S22 simply didn't need the bandwidth and the scheduler took the path of least resistance – it sent a lot of data over the otherwise unused 20 MHz of FDD spectrum on Band n25.

Figure 13. Total 5G PDSCH Throughput Time Series – by UE



Source: Signals Research Group

Figure 14. Distribution of Average 5G PDSCH Throughput – by UE and Component Carrier

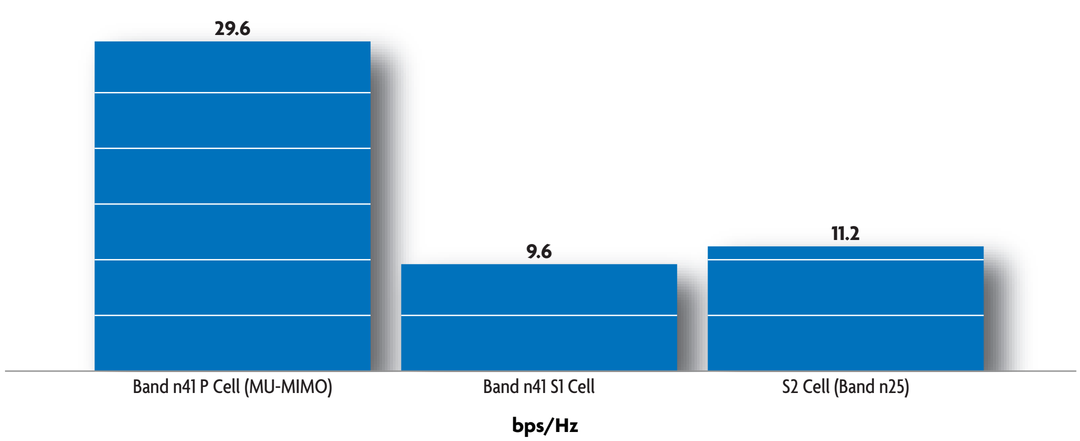


Source: Signals Research Group

Finally, Figure 15 shows the calculated spectral efficiency for the three 5G carriers, although the results for Band n25 stem from a single smartphone. We also believe the spectral efficiency for the two Band n41 carriers, in particular the S1 Cell results, are slightly understated and that using a larger data transfer speed to each smartphone would have improved the spectral efficiency even further. Nonetheless, the increase in spectral efficiency due to MU-MIMO is impressive. Readers shouldn't expect these results in absolute terms when we publish the full set of results in the forthcoming Signals Ahead, but it wouldn't surprise us if the outcome is comparable on a relative basis (e.g., the gains from MU-MIMO can be impressive).

The increase in spectral efficiency due to MU-MIMO is impressive.

Figure 15. Spectral Efficiency – by 5G Component Carrier



Source: Signals Research Group

TEST METHODOLOGY

For purposes of this section, we'll just discuss the steps we took when collecting and analyzing the tests shown in this Signals Flash! In our forthcoming Signals Ahead report we will expand this section to discuss other steps we took when collecting and analyzing the MU-MIMO results.

Consistent with virtually all our 5G benchmark studies, we collaborated with Accuver Americas and Spirent Communications – two trusted partners that we have worked with for nearly 15 years. We used XCAL5 to collect the chipset diagnostic messages and we used the XCAP post-processing tool to analyze the results. Spirent Communications provided its Umetrix Data platform which we used to generate the high bandwidth data transfers to each smartphone.

We collaborated with Accuver Americas and Spirent Communications – two trusted partners that we have worked with for nearly 15 years.

We used up to four notebook computers to log chipset data – more PCs allowed us to get greater separation of the smartphones and CPEs in outdoor testing – but for the test shown in this report we used two PCs with two smartphones attached to each computer. We didn't put any thought into the placement of the smartphones to maximize MU-MIMO pairing but we at least confirmed the four smartphones were using the same PCI.

We used Umetrix Data to load the network and for this test we used a 750 Mbps UDP profile. Each test lasted 5 minutes and then automatically repeated. In this test, and in most tests, we conducted, we started the data transfers in a serial fashion so that one, two, three and ultimately four phones were attached to the network and receiving data. With four phones, each receiving 750 Mbps at the application layer there was sufficient throughput at the physical layer to load Band n41, even with MU-MIMO. However, we subsequently discovered one of the phones in this test also used Band n25 as a secondary carrier (S2 Cell), which we believe resulted in somewhat lower MU-MIMO performance in the P Cell, not to mention lower spectral efficiency in the Band n41 40 MHz S1 Cell. One other impact of using a 750 Mbps profile is that the achieved throughput with a single UE attached to the network was artificially limited relative to the capabilities of the radio channel, even without MU-MIMO pairing. For this analysis, we knew that a single smartphone could achieve an average throughput of 1.3 Gbps in the P Cell, so we used that value for comparative analysis. In other tests we did during the week we used a higher throughput profile from Umetrix Data, especially when looking at the pairing of two smartphones, each using 4 layers.

We analyzed the data in one second time increments. As a first step we made sure all smartphones were sharing the same PCI (cell site) and, of course, using Band n41. We analyzed what we felt were the most important metrics when doing the analysis, including RB usage, MIMO layers, MCS values, and PDSCH throughput. We may also include SRS-related metrics in our forthcoming Signals Ahead report.

Unlike the case with our LTE MU-MIMO study when we knew a smartphone using transmission mode 8 (TM8) and a single MIMO layer was almost certainly pairing, we didn't have any obvious metric to confirm pairing was occurring. Seeing SRS metrics in the uplink was a requisite for SRS and SRS is a requisite for SRS-based MU-MIMO, but it is possible to have a smartphone use SRS without using MU-MIMO. Instead, we looked at RB utilization, specifically "RB incl 0" utilization, which inherently takes into consideration RBs being allocated to other UEs. This metric is markedly different from RB Avg where no insight into unscheduled RBs/slots is provided.

We looked at RB utilization, specifically "RB incl 0" utilization, which inherently takes into consideration RBs being allocated to other UEs,

With the TDD frame structure used by T-Mobile we knew the maximum value of the RB Incl 0 parameter so if the smartphone reached the number, then we knew it was getting all the available

RBs. If two smartphones simultaneously reported reaching this maximum value (in one second time bins) then we knew the two devices had 100% efficient MU-MIMO pairing. If the summation of the two RB Incl 0 values fell somewhere in between the maximum value with a single UE and 2x this value, then we knew MU-MIMO pairing occurred but not in all possible slots and with all RBs.

We took a somewhat similar approach with MIMO layer counts – a metric that was also binned in one second time increments. Today's 5G smartphones support up to 4 MIMO layers while with 8 layer MU-MIMO the total number of layers supported by the network increases to 8 layers, shared across up to 8 devices. Simply adding up the MIMO layer count across devices would result in an erroneous representation of the total number of layers since the logic used to calculate the average number of layers doesn't consider the UEs can share RBs. Therefore, we weighted the reported MIMO layer count by the RB incl 0 efficiency. For example, if the MIMO layer count was 2 and the UE with MU-MIMO pairing only used half the possible RBs (suggesting 50% pairing efficiency) then the MIMO Layer Count (RB adj) value would be 1. In our opinion, using the RB adjusted MIMO Layer Count is the best means of gauging MU-MIMO pairing efficiency since the efficiency is determined by the reuse of the resource block while maintaining the same MIMO layer count.

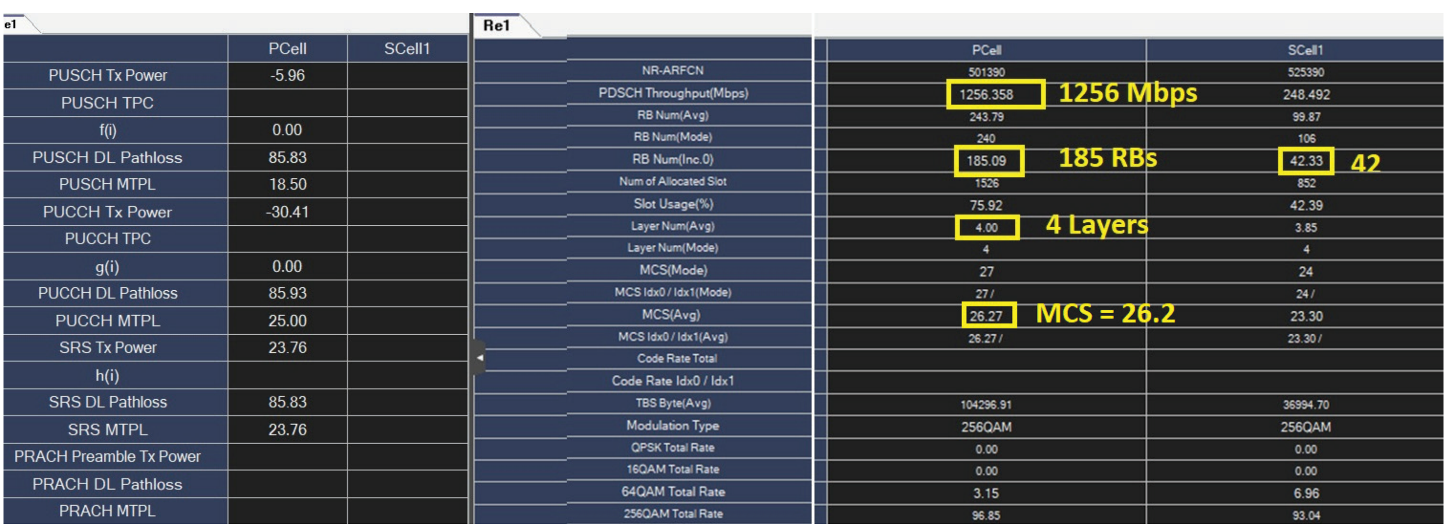
We used RB adjusted MIMO Layer counts to gauge the true efficiency of MU-MIMO pairing.

Of course, the truest measurement stick of MU-MIMO performance is its impact on total throughput/spectral efficiency. If MU-MIMO pairing is only achieved with a subsequent drop in the MCS value, then nothing is gained. Therefore, we looked at the average MCS values before and during MU-MIMO pairing as well as the increase in the total throughput of the P Cell where the MU-MIMO pairing occurred.

The truest measurement stick of MU-MIMO performance is its impact on total throughput/spectral efficiency.

Figure 16 shows a screen shot of the XCAL GUI during a separate test involving two UEs, each doing a 1.5 Gbps data transfer. Worth noting, this screen shot was taken when the smartphone was pairing with a second adjacent smartphone, which was achieving similar performance. The left side of the figure shows the SRS parameters which are only reported by smartphones that support SRS functionality. Finally, Figure 17 showcases the Umetrix Data platform and architecture. For these tests, we used a Umetrix high bandwidth server located in California, although we've used servers located on the East Coast, Midwest, Europe, and Asia, depending on where we were doing the testing,

Figure 16. XCAL5 in Action

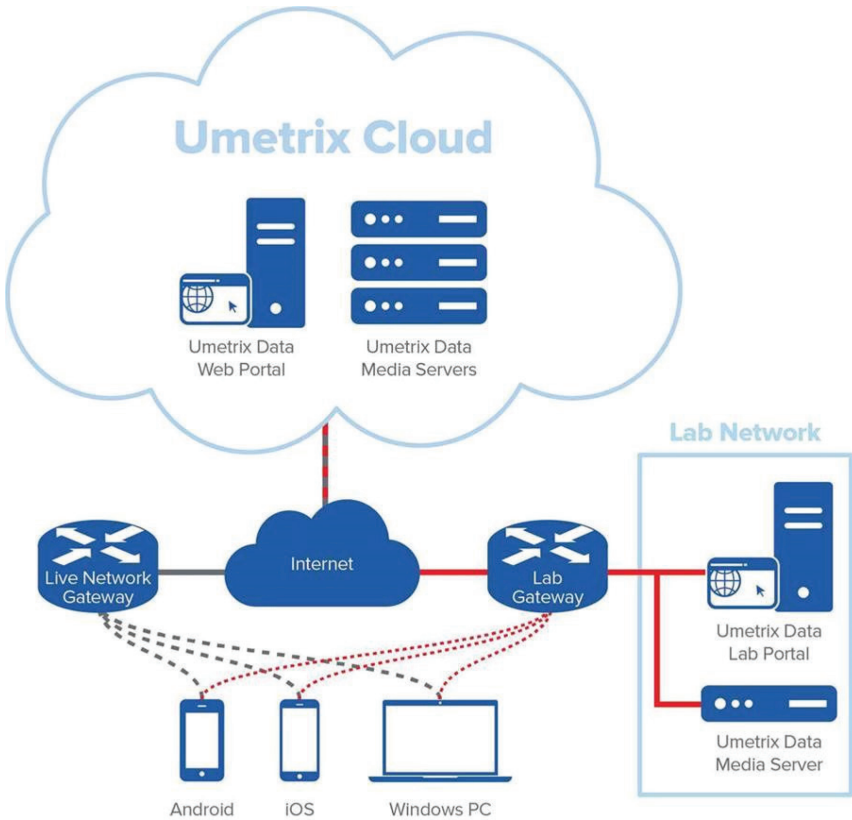


	PCell	SCell1
PUSCH Tx Power	-5.96	
PUSCH TPC		
f(i)	0.00	
PUSCH DL Pathloss	85.83	
PUSCH MTPL	18.50	
PUCCH Tx Power	-30.41	
PUCCH TPC		
g(i)	0.00	
PUCCH DL Pathloss	85.93	
PUCCH MTPL	25.00	
SRS Tx Power	23.76	
h(i)		
SRS DL Pathloss	85.83	
SRS MTPL	23.76	
PRACH Preamble Tx Power		
PRACH DL Pathloss		
PRACH MTPL		

	PCell	SCell1
NR-ARFCN	501390	525390
PDSCH Throughput(Mbps)	1256.358	248.492
RB Num(Avg)	243.79	99.87
RB Num(Mode)	240	106
RB Num(Inc.0)	185.09	42.33
Num of Allocated Slot	1526	852
Slot Usage(%)	75.92	42.39
Layer Num(Avg)	4.00	3.85
Layer Num(Mode)	4	4
MCS(Mode)	27	24
MCS Idx0 / Idx1(Mode)	27 /	24 /
MCS(Avg)	26.27	23.30
MCS Idx0 / Idx1(Avg)	26.27 /	23.30 /
Code Rate Total		
Code Rate Idx0 / Idx1		
TBS Byte(Avg)	104296.91	36994.70
Modulation Type	256QAM	256QAM
QPSK Total Rate	0.00	0.00
16QAM Total Rate	0.00	0.00
64QAM Total Rate	3.15	6.96
256QAM Total Rate	96.85	93.04

Source: Signals Research Group

Figure 16. Umetrix Data Platform



Source: Spirent Communications

Michael Thelander

Michael Thelander is the President and Founder of Signals Research Group (SRG), a US-based research consultancy that offers thought-leading field research and consulting services on the wireless telecommunications industry.

Its flagship research product is a research product entitled Signals Ahead, which has attracted a strong following across the entire wireless ecosystem with corporate subscribers on five continents. SRG's Signals Ahead research product and its consulting services are technology-focused with a strong emphasis on next-generation networks and performance benchmarking.

In his current endeavor, Mr. Thelander is the lead analyst for Signals Ahead and he guides a team of industry experts that provide consulting services for the wireless industry, including some of the largest mobile operators, the top equipment OEMs, trade associations, and financial institutions. He has also served as a member of an industry advisory board for one of the world's largest wireless infrastructure suppliers.

Mr. Thelander earned a Masters of Science in Solid State Physics from North Carolina State University and a Masters of Business Administration from the University of Chicago, Graduate School of Business.

Emil Olbrich

Emil Olbrich is currently VP of Networks with Signals Research Group. Prior to this he was head of LTE research, development, test and evaluation for the Public Safety Communications Research Program where he deployed the first and most diverse Public Safety 700 MHz LTE test lab in the world with over 70 participating vendors and commercial carriers. He was responsible for the specifying, deploying and maintaining the entire ecosystem of LTE which included devices, air interface, transport, radio access network, evolved packet core, IP networking, IMS core and application servers. He also led the team efforts, which include standards work, test case development and test case execution.

Mr. Olbrich has over 20 years of experience in the field of wireless telecommunications. He has worked primarily in R&D at some of the largest telecommunication companies in the world - such as Motorola, Qualcomm and Ericsson. His scope of work includes deploying and operating LTE infrastructure (RAN, EPC and IMS) from numerous Tier 1 vendors; testing new LTE mobile devices from multiple suppliers; testing, deploying and operating some of the first commercial CDMA networks; serving as Lead Project engineer for the 2002 Salt Lake City Winter Olympics and as the Project Manager for the China Ministry of Information Industry 3G testing in China; and supporting the early development of HDR (EV-DO and EV-DO Rev A).

He has been a speaker at events such as the GSMA Mobile World Congress, LTE North America, 4G World, International Wireless Communications Expo and LTE World Summit. Mr. Olbrich has a B.S. degree in Electrical Engineering Technology from Southern Illinois University.

ON THE HORIZON: POTENTIAL *SIGNALS AHEAD/SIGNALS FLASH!* TOPICS

We have identified a list of pending research topics that we are currently considering or presently working on completing. The topics at the top of the list are definitive with many of them already in the works. The topics toward the bottom of the page are a bit more speculative. Obviously, this list is subject to change based on various factors and market trends. As always, we welcome suggestions from our readers.

5G Standardization

- *5G from a 3GPP Perspective (ongoing series of reports – published quarterly or as warranted)*

Thematic Reports

- *Mobile Edge Computing and the impact of data caching at the cell edge*

Benchmark Studies

- *5G NR mmWave Fixed Wireless Access with IAB*
- *SRS versus codebook beamforming benchmark study*
- *Mobile Edge Computing*
- *Open RAN network performance benchmark study 1 – Dish Network Revisit*
- *Open RAN network performance benchmark study 3 – Scheduling Efficiency*
- *FR1 + FR2 NR-DC network performance benchmark study*
- *MU-MIMO benchmark study (FR1)*
- *High Power User Equipment (HPUE) benchmark study*
- *SRS-based beamforming benchmark study*
- *5G mmWave device/chipset lab-based benchmark study*
- *DSS Update benchmark study*

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