5G MULTI-USER MIMO – IT ISN'T JUST FOR DOWN-LINK ANYMORE

A THIRD-PARTY BENCHMARK STUDY OF 5G DOWN-LINK AND UPLINK MU-MIMO IN A COMMERCIAL NETWORK

February 2024

Prepared by
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Study Conducted for Samsung Networks

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 nearly two decades.

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 Multi-User MIMO (MU-MIMO) in a commercial 5G network. We leveraged the Verizon 5G network (Band n77), using O-RAN interface 7-2x, in suburban Dallas, Texas where Samsung Networks is the virtualized RAN and Massive MIMO radio supplier. By using up to eight Samsung Galaxy S23 smartphones in a wide range of test scenarios we were able to quantify the potential capacity gains that are possible with MU-MIMO in both the downlink and uplink directions.

The cell site where we did our tests supported sixteen MIMO layers in the downlink direction and four MIMO layers in the uplink direction. For comparison purposes, single-user MIMO (SU-MIMO) is limited to four downlink layers and one uplink layer in a 5G Non-Standalone (NSA) network or two uplink layers in a 5G SA network. Since each MIMO layer introduces an additional data stream in the network, the use of more MIMO layers in both directions inherently increases capacity, spectral efficiency and improves network economics. Depending on the cell site configuration, Samsung Networks supports up to eight MIMO layers in the uplink direction, suggesting even better performance than what we identify in this paper.

Key highlights from our benchmark testing include the following:

- **Triple Digit Downlink Capacity Gains.** Downlink MU-MIMO with support for up to sixteen MIMO layers increased cell sector capacity by up to 3.2x over sustained time intervals, compared with SU-MIMO. With MU-MIMO, we documented average cell sector throughput of nearly 3 Gbps on a single 100 MHz Band n77 channel, or a spectral efficiency of 36.4 bps/Hz – even more impressive when considering all testing occurred in a commercial network. For comparison purposes, the average throughput with SU-MIMO from the identical test locations was just over 900 Mbps on the same 100 MHz channel.

- **High Reuse of Downlink Network Resources.** The downlink MU-MIMO capacity gains stemmed from high reuse of network resource blocks (RBs) and MIMO layers. The capacity gains cited in the previous bullet, for example, involved a near-perfect reuse of all available RBs by the eight smartphones used in the test (7.7x increase versus SU-MIMO). Likewise, we observed an average of 13 MIMO layers in this particular test, and up to the theoretical 16 MIMO layers in another test scenario.

- **Triple Digit Uplink Capacity Gains**. We observed similar, if not more impressive, gains in uplink capacity due to MU-MIMO. With four smartphones simultaneously transmitting data, the total uplink throughput reached nearly 300 Mbps, equating to a spectral efficiency of 14.4 bps/Hz. These results compare with 86 Mbps and 4.3 bps/Hz, respectively, with SU-MIMO, or a capacity gain of 3.3x.

- **High Reuse of Uplink Network Resources.** With uplink MU-MIMO, the network resource block allocations increased by an average of 3.3x and the number of uplink MIMO layers increased by 3.6x, compared with SU-MIMO. Even higher reuse is likely possible with a network configuration that supports Samsung's implementation of 8 layer uplink MU-MIMO.

- **Good Resilience with more Challenging Test Scenarios.** We conducted several downlink and uplink test scenarios, including a test with a mix of phones doing downlink or uplink data transfers, with some of the phones positioned hundreds of meters from the cell site and/or located close to each other. Results from these tests also showed high capacity gains reaching into the low triple digits on a percentage basis. We also observed that if a phone's poor location prevented it from pairing, the other phones in the test continued to pair with each other, thereby delivering much higher throughput than possible with SU-MIMO.

- **More MIMO Layers are a Good Thing.** Although it isn't always possible for a 5G network to use a high number of MIMO layers, a network that supports sixteen downlink layers and four, or even eight, uplink layers will have an inherent performance advantage over a network that supports fewer MIMO layers, and especially versus SU-MIMO. In comparative tests with four phones and eight phones, the results with eight phones were always higher than the tests with four phones. Further, in all our MU-MIMO tests the average MIMO layer count frequently exceeded eight layers.

- **MU-MIMO is critical to the FWA use case.** MU-MIMO is most beneficial to the fixed wireless access (FWA) use case since the end user devices are in a fixed location and the data consumption is generally higher than the mobile broadband use case.

The following sections of this paper support the comments made in this executive summary. We start off with a 5G MU-MIMO Primer section which summarizes important concepts pertaining to SU-MIMO and MU-MIMO. Given the large number of tests we conducted for this study, we include detailed results for two representative downlink and two representative uplink MU-MIMO test cases in the main body of the report with the remaining test cases documented in an expansive appendix. Preceding the appendix, we document how we conducted the tests and analyzed the results in a Test Methodology section. We also include some background information about Signals Research Group and our experiences with conducting benchmark studies.

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5G MU-MIMO Primer

SU-MIMO and MU-MIMO are similar in that with certain radio conditions they can reuse the same resource in the time and frequency domain, resulting in higher data speeds and 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 are introduced while the requisite pristine conditions are rarely achieved.

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.

The 16-layer downlink MU-MIMO implementation we tested in the Verizon network used a flavor of MU-MIMO which leverages SRS (Sounding Reference Signal). 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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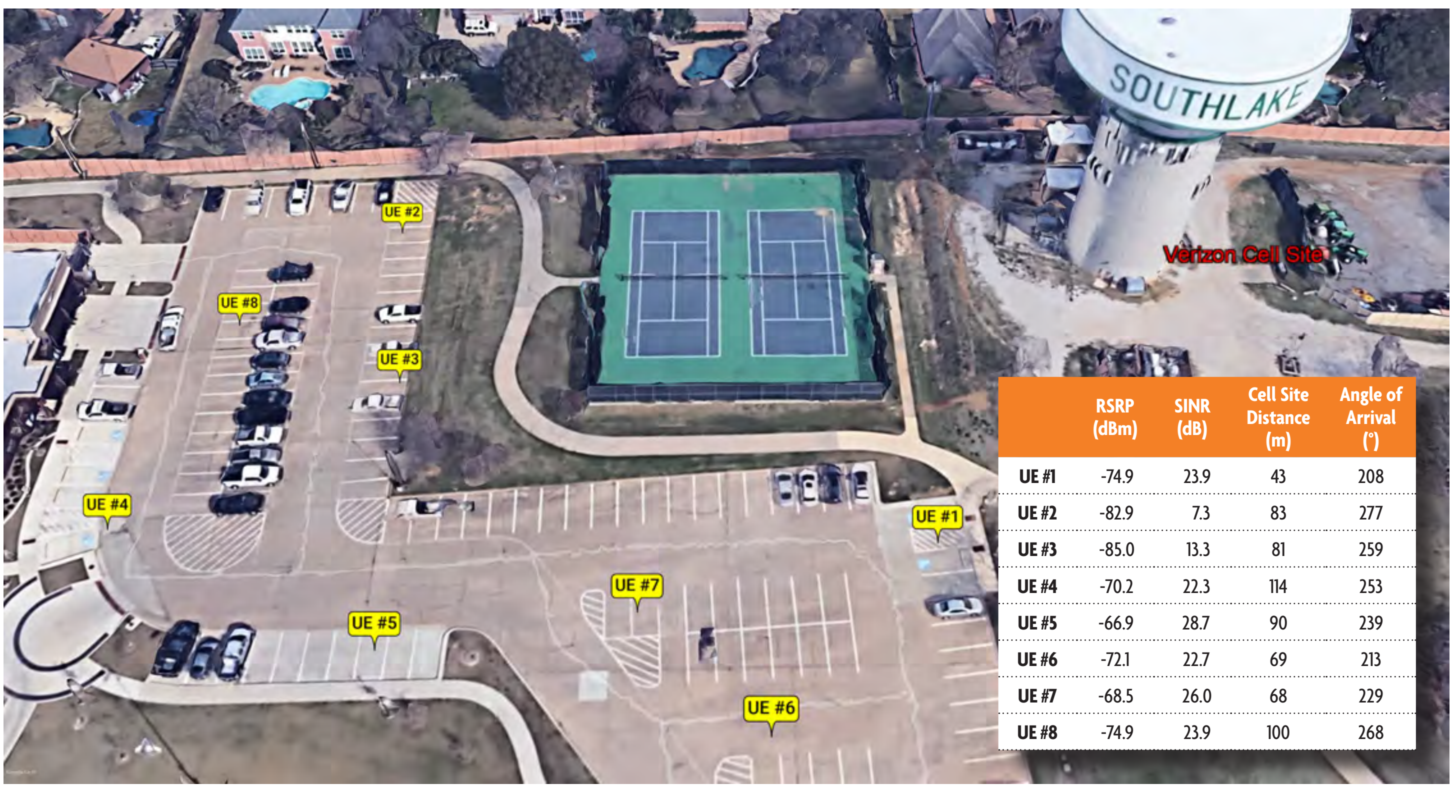
SRS-based MU-MIMO is limited, at least for now, to the primary cell (P Cell). Therefore, the results in this whitepaper are specific to the P Cell. In the appendix, we include results for one test scenario in which we also show the performance of the secondary cell (S Cell), which in this case was a 40 MHz channel, also using Band n77.

Downlink MU-MIMO can significantly increase downlink capacity with a wide range of use cases and deployment scenarios

We conducted multiple downlink data tests involving four to eight mobile phones within a single cell sector. We included scenarios with mobile phones located relatively close to the cell site as well as scenarios with mobile phones located both near and far from the cell site. In our tests, we first quantified the performance of the network with SU-MIMO and then with MU-MIMO (e.g., all smartphones simultaneously downloading data). We include two representative scenarios in this section and several additional test scenarios in the appendix.

Figure 1 identifies the locations of eight mobile phones in the parking lot adjacent to the serving cell site. This test scenario reflects relatively ideal conditions for MU-MIMO although we note we didn't spend much time positioning the mobile phones from their initial locations. While all mobile phones were relatively close to the cell site, in many cases there was only a minor angular separation between phones. Although we tested from the parking lot adjacent to the cell site, it is easy to envision a scenario in which the cell site is located within a stadium or at another location with lots of nearby data traffic. From an RF perspective, our test scenario mirrors those scenarios so the results between the two deployment scenarios should be similar.

Figure 1. Test Case 6 Mobile Phone Locations and Key RF Metrics



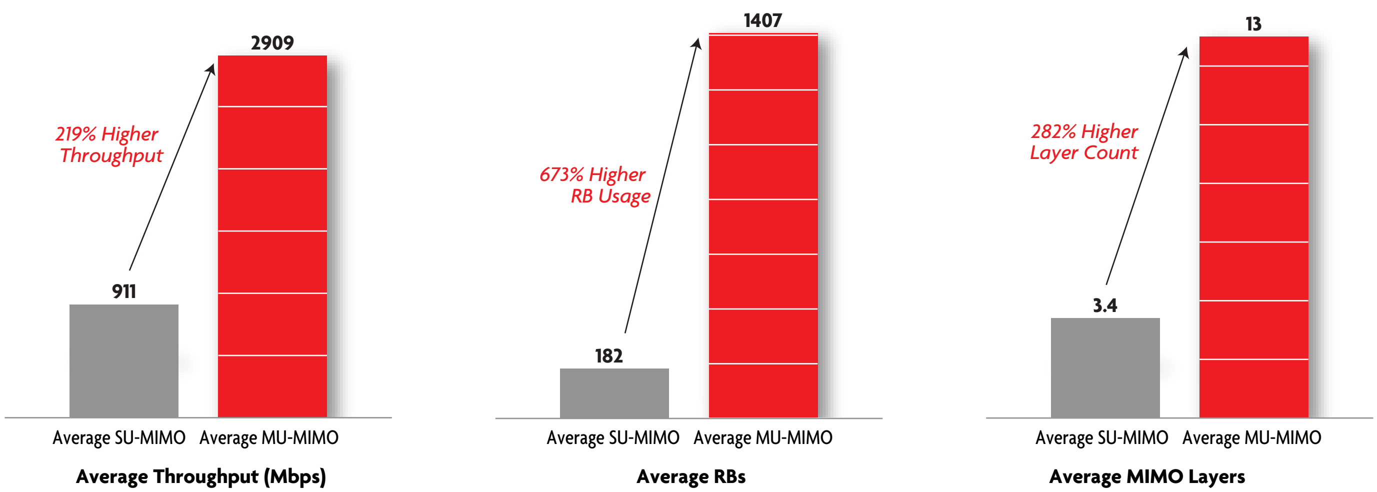
	RSRP (dBm)	SINR (dB)	Cell Site Distance (m)	Angle of Arrival (°)
UE #1	-74.9	23.9	43	208
UE #2	-82.9	7.3	83	277
UE #3	-85.0	13.3	81	259
UE #4	-70.2	22.3	114	253
UE #5	-66.9	28.7	90	239
UE #6	-72.1	22.7	69	213
UE #7	-68.5	26.0	68	229
UE #8	-74.9	23.9	100	268

Source: Signals Research Group

Since we were testing in a commercial network during normal daytime hours, it wasn't feasible to enable and disable MU-MIMO functionality. Instead, we calculated SU-MIMO performance by testing each mobile phone by itself from its location and then averaging the results across all mobile phones. We then conducted the same test with all smartphones transferring data in parallel to achieve the MU-MIMO results. Figure 2 provides a summary of the results from this particular test scenario. The comparative throughput result is the most important metric since it defines the potential increase in total sector throughput due to MU-MIMO. For this test, the total throughput in the primary cell (P Cell) increased by 220% from 911 Mbps with SU-MIMO to 2,909 Mbps with MU-MIMO. The other two comparisons help explain how the increase in throughput was achieved. Specifically, due to resource block (RB) pairing, the total RB allocations for all phones increased by 672%. Likewise, the total number of MIMO layers increased from an average of 3.4 layers to 13 layers.

The total throughput in the P Cell increased by 220% from 911 Mbps with SU-MIMO to 2,909 Mbps with MU-MIMO.

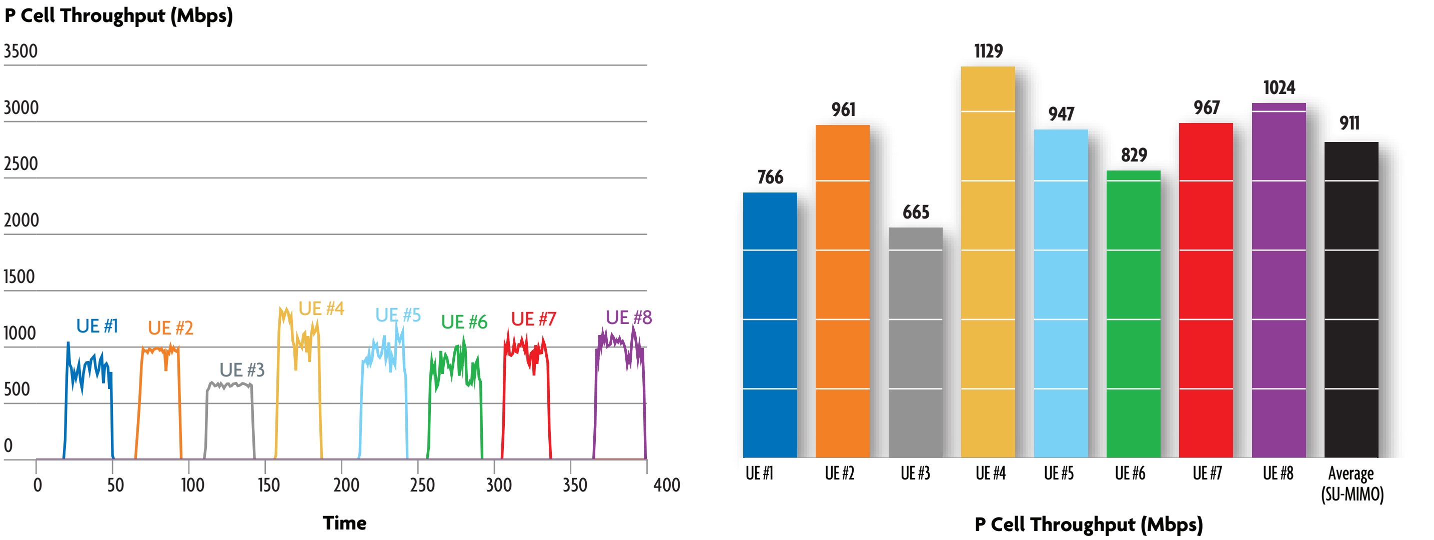
Figure 2. Summary of Results



Source: Signals Research Group

The next several figures provide additional details on the SU-MIMO and MU-MIMO results for this test scenario, and they help illustrate our test procedure, as well as how we analyzed the data. Figure 3 provides a time series plot of the P Cell PDSCH throughput for each smartphone along with the average for each smartphone. For all eight phones, the average downlink throughput was 911 Mbps. In other words, if we had downloaded data to each smartphone simultaneously with MU-MIMO disabled then we assume the total [SU-MIMO] throughput for all eight smartphones would have been 911 Mbps.

Figure 3. SU-MIMO Throughput



Source: Signals Research Group

We did two MU-MIMO tests with all eight smartphones, as shown in Figure 4. The average total throughput for the two tests was 2,909 Mbps, or 220% higher than the SU-MIMO outcome of 911 Mbps. Assuming an 80/20 split between the downlink and uplink in the 100 MHz Band n77 channel, the spectral efficiency with MU-MIMO was a very impressive 36.4 bps/Hz, compared with "only" 11.4 bps/Hz with SU-MIMO.

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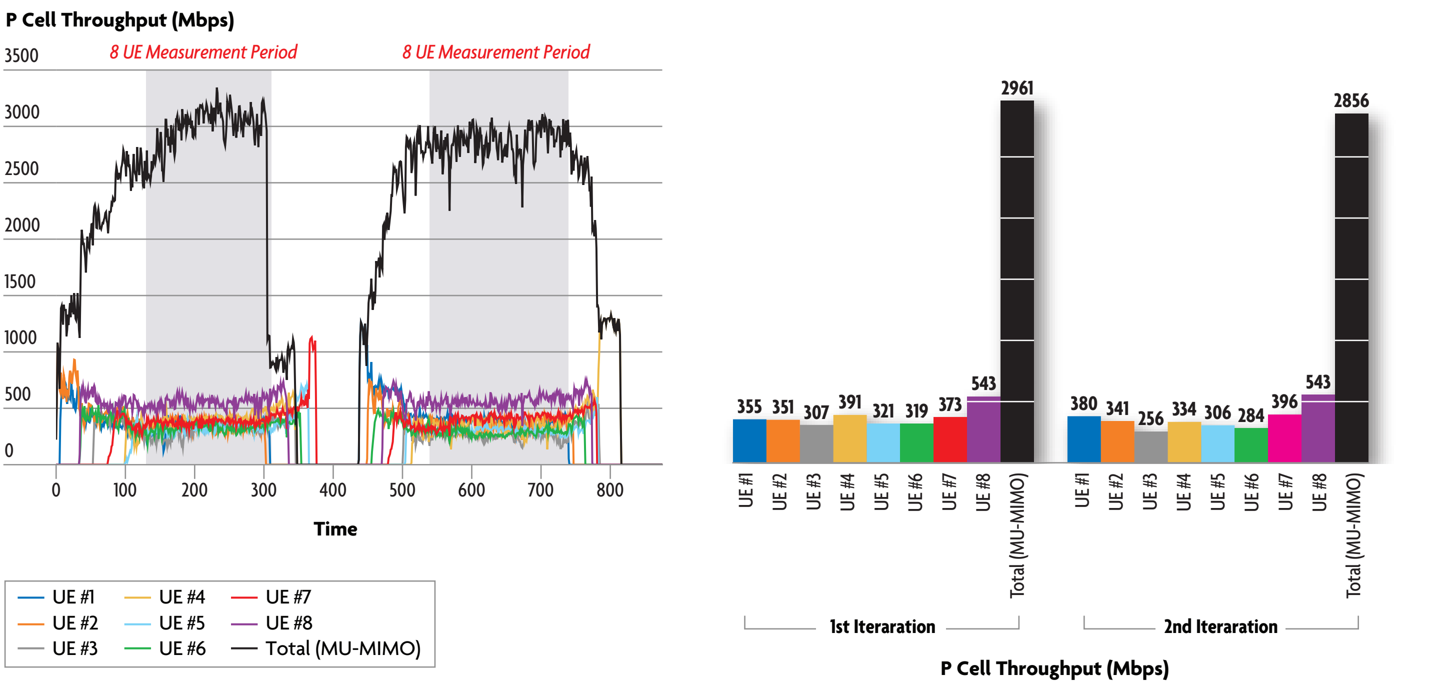
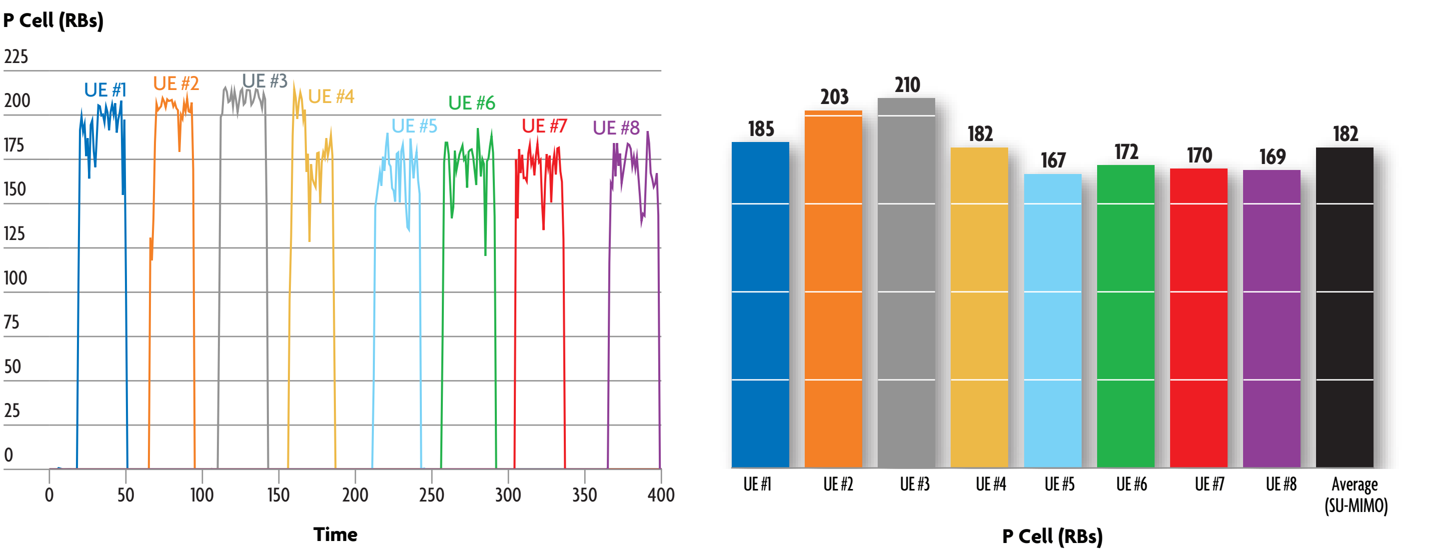
Figure 4. MU-MIMO Throughput



Source: Signals Research Group

Figure 5 shows how the network allocated resource blocks (RBs) to the smartphones during the SU-MIMO tests. On average, the smartphones used 182 RBs, which is close to the maximum RB allocation of ~210 RBs that we observed in the log files. It is very likely the dips in the colored lines showing each smartphone's RB allocations were caused by other mobile data users in the network. This situation impacted both the SU-MIMO and MU-MIMO results, but it was unavoidable.

Figure 5. SU-MIMO Resource Block Allocations

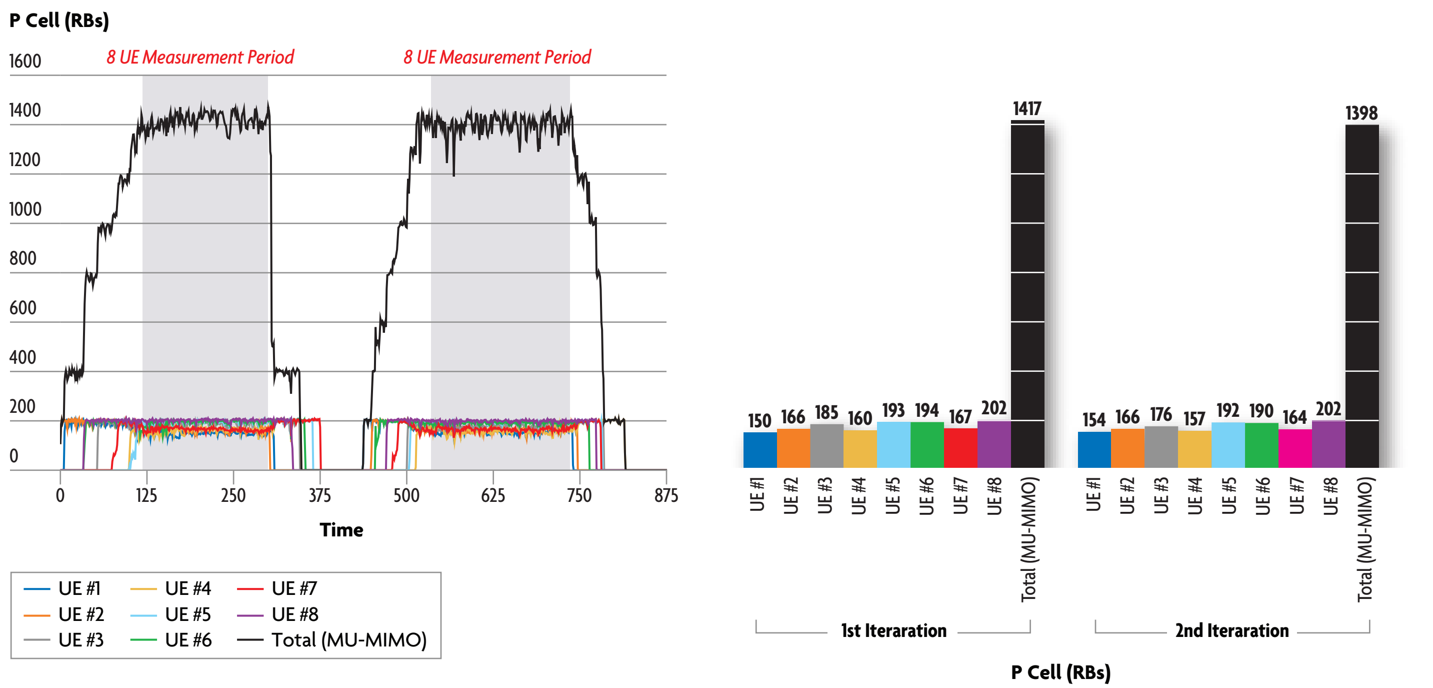


Source: Signals Research Group

Figure 6 provides the RB allocations during the MU-MIMO tests. The time series figure clearly shows that as each smartphone began its downlink data transfer, the number of total RBs increased since MU-MIMO pairing allows for smartphones to reuse the same RB, thus leading to the capacity gains we showed earlier in Figure 2.

MU-MIMO pairing allows for smartphones to reuse the same RB, thus leading to capacity gains in the network.

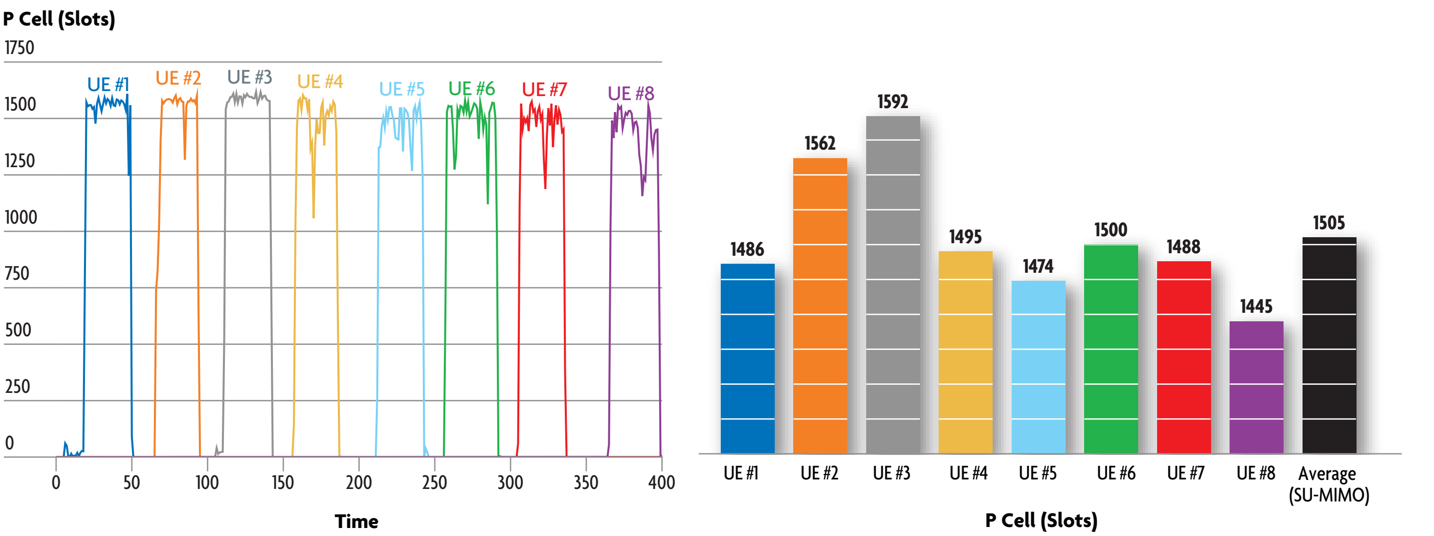
Figure 6. MU-MIMO Resource Block Allocations



Source: Signals Research Group

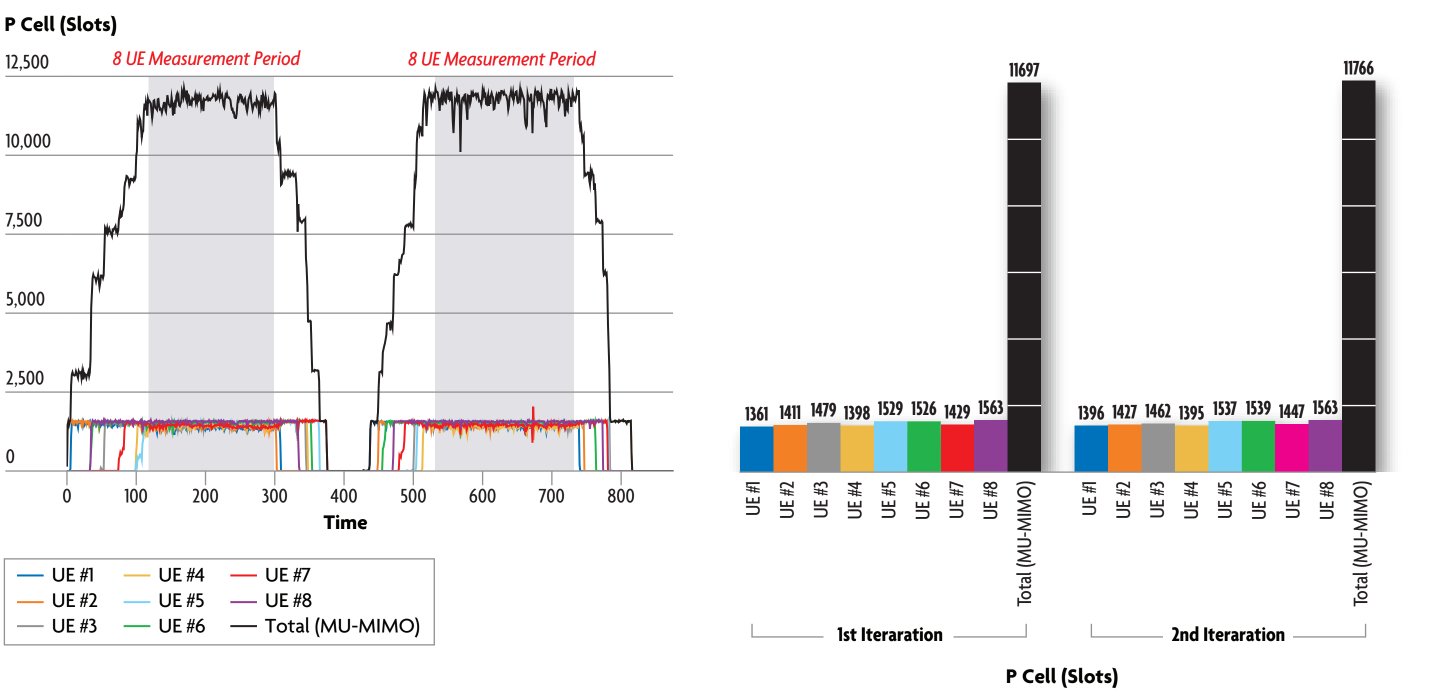
An RB is defined by a frequency component and a time component, or time slot. Since MU-MIMO enables the sharing of RBs, it is only logical that MU-MIMO also results in the sharing of time slots. Although a bit redundant given the earlier RB figures, Figure 7 (SU-MIMO) and Figure 8 (MU-MIMO) provide comparative results for the use/reuse of time slots between SU-MIMO and MU-MIMO.

Figure 7. SU-MIMO Time Slot Allocations



Source: Signals Research Group

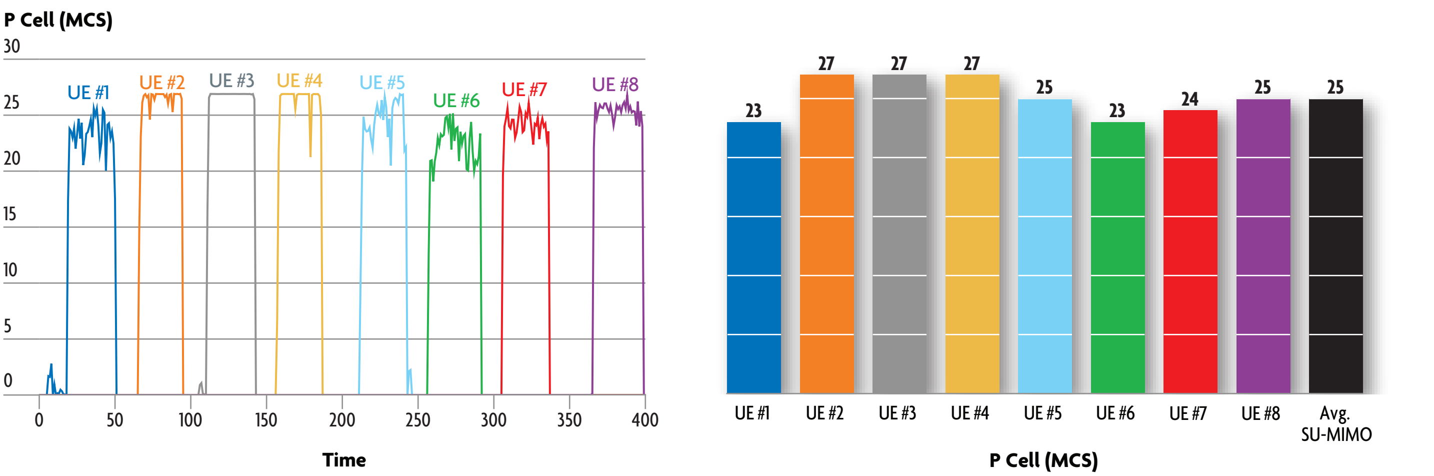
Figure 8. MU-MIMO Time Slot Allocations



Source: Signals Research Group

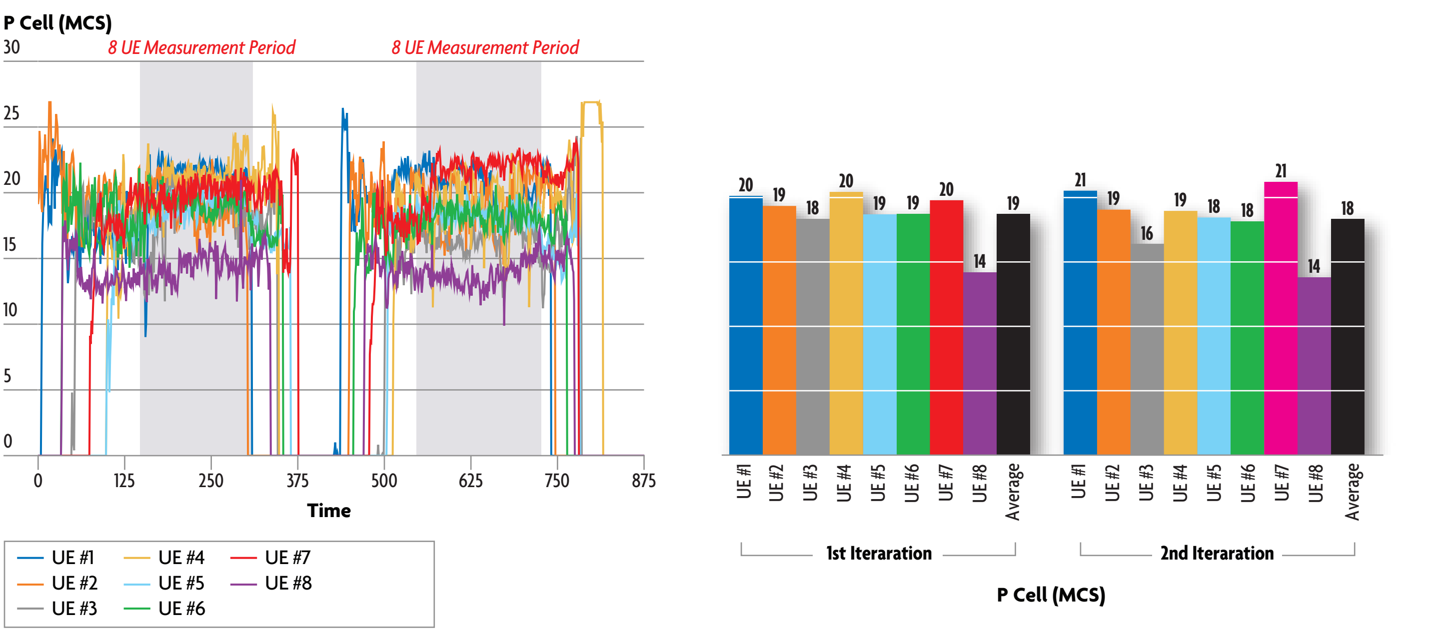
The modulation and coding scheme (MCS) defines how much data, or data bits, can be transmitted by a single resource element (RE), which is a sub-unit of a resource block. Higher MCS values, along with higher RB allocations and MIMO layers result in higher throughput. The MCS values, which range from 0 to 27, do not specifically identify the amount of data being transmitted. Instead, the MCS values reference detailed lookup tables within the 5G standard that define the amount of data (transport block size) being sent for the given MCS, RB allocation, and layer count. Figure 9 (SU-MIMO) and Figure 10 (MU-MIMO) show the results from the two tests. There was some expected decline in the MCS values with MU-MIMO, but the net effect was still a substantial increase in total throughput which is the primary objective of MU-MIMO.

Figure 9. SU-MIMO MCS Allocations



Source: Signals Research Group

Figure 10. MU-MIMO MCS Allocations



Source: Signals Research Group

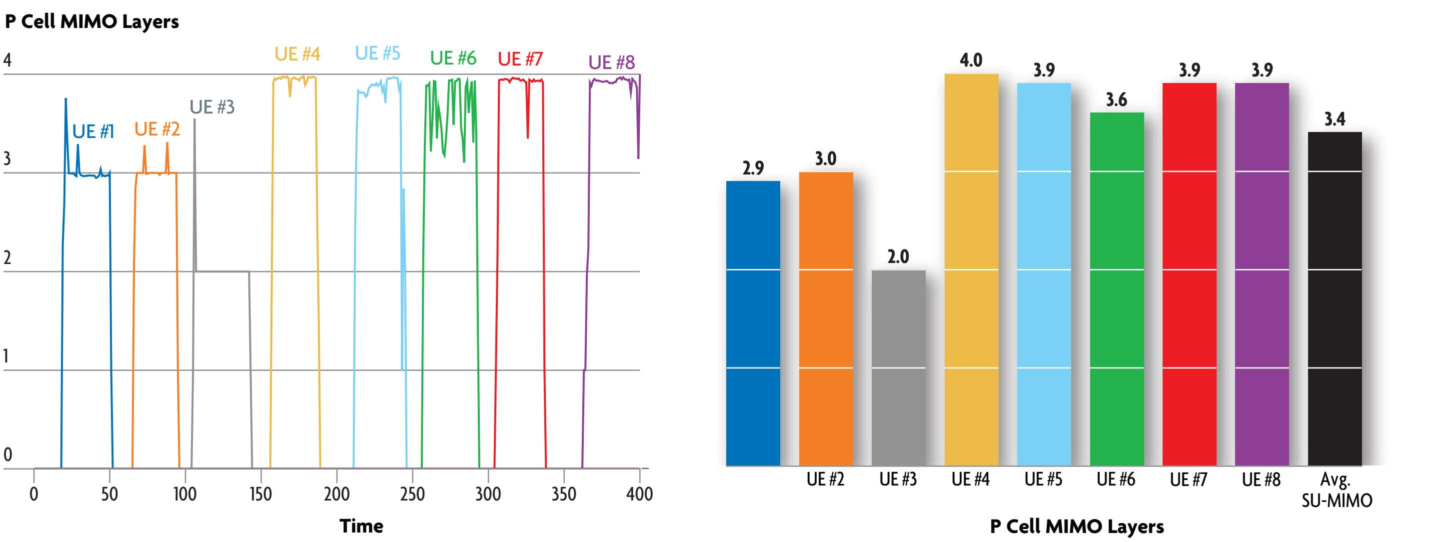
In today's 5G networks, smartphones are limited to no more than four SU-MIMO layers. In theory and all else being equal, two SU-MIMO layers provide twice the throughput as a single SU-MIMO layer and four SU-MIMO layers provide twice the throughput as two SU-MIMO layers, or four times the throughput of a single SU-MIMO layer. MU-MIMO doesn't increase the layer count for an individual smartphone – they are still limited to four layers – but it does allow for the network to support more simultaneous MIMO layers across the network. With the network configuration we tested as part of this study, the network supported up to sixteen simultaneous downlink layers, meaning four phones can each achieve four SU-MIMO layers, eight phones can each achieve two SU-MIMO layers, etc.

MU-MIMO doesn't increase the layer count for an individual smartphone, but it does allow for the network to support more simultaneous MIMO layers across the network.

If we compare the results from the two tests, it is evident that most of the smartphones could support four MIMO layers when tested individually (Figure 11). UE #3 was limited to two MIMO layers, but it also used a higher MCS than most of the phones during the SU-MIMO test. When testing all eight phones together, the total MIMO layer count increased to an average of over thirteen layers with a maximum of over fourteen MIMO layers achieved several times during the two tests. Each phone's layer count did drop relative to the SU-MIMO tests, but this is an expected outcome with MU-MIMO since the phones were also sharing network resources (RBs). Put another way, with SU-MIMO and all eight phones transferring data simultaneously, many of the phones might have used four MIMO layers, but they would have been using far fewer RBs since they would be sharing the RBs with other active smartphones, and their throughput would have been much lower, as indicated in Figure 2. In the appendix, we show comparative results for the 5G primary cell (MU-MIMO) and 5G secondary cell (SU-MIMO) to illustrate this point.

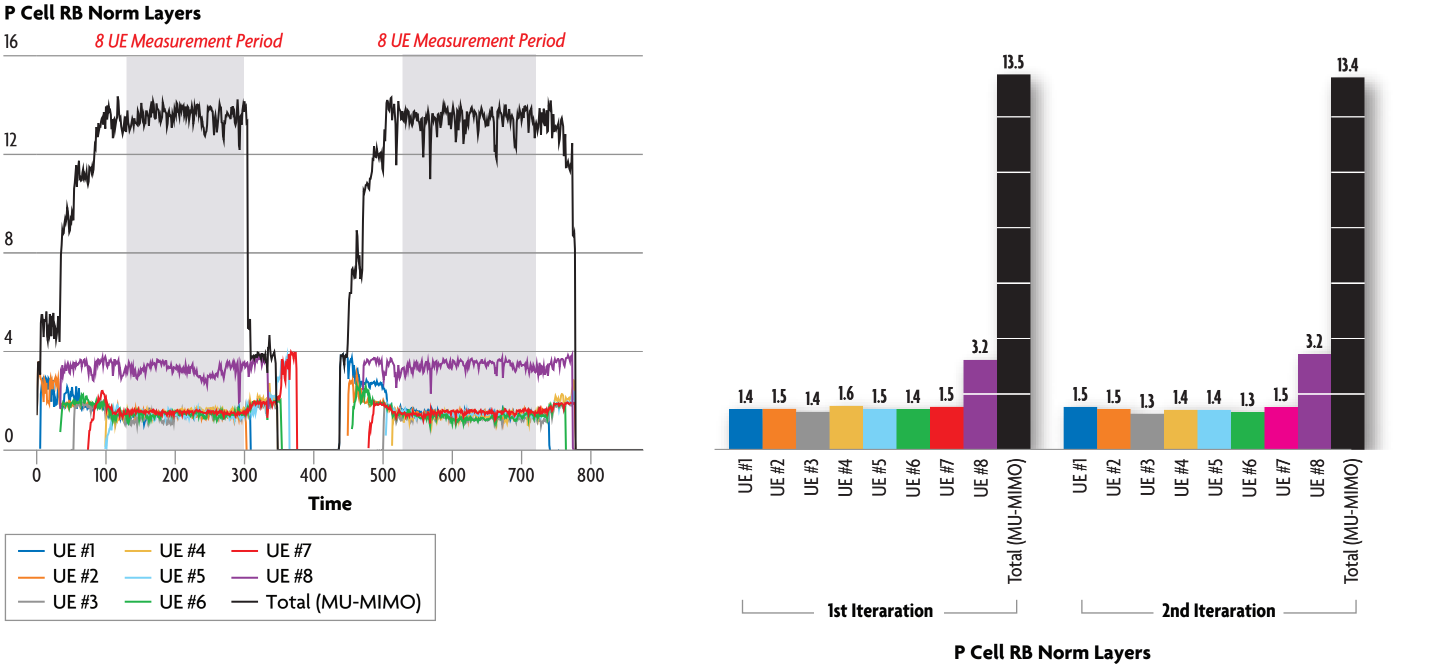
There was an average of over thirteen MIMO layers and a maximum of over fourteen MIMO layers with this test scenario.

Figure 11. MIMO Layers with SU-MIMO



Source: Signals Research Group

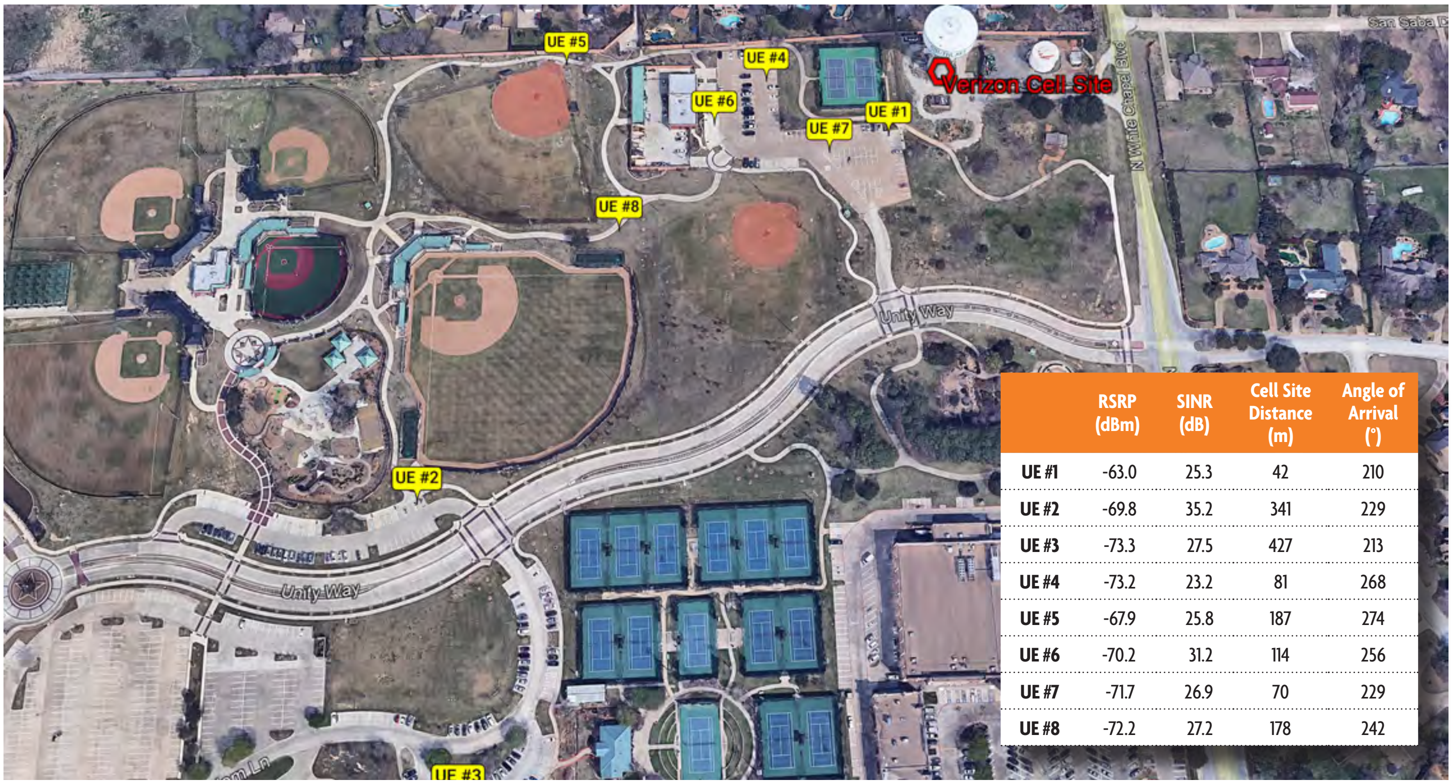
Figure 12. MIMO Layers with MU-MIMO



Source: Signals Research Group

We are including one more downlink MU-MIMO study in this section, with additional test results in the appendix. For this test, we once again used eight smartphones, but we moved four of the smartphones much further away from the cell site, including two smartphones near one of the ball diamonds and two smartphones in two separate parking lots up to more than 425 meters from the serving cell site (Figure 13). Given the near-far placements of the phones, the horizontal angular separation between some of the smartphones was very tight, potentially making it more difficult for the smartphones to achieve MU-MIMO pairing.

Figure 13. Test Case 16 Mobile Phone Locations and Key RF Metrics



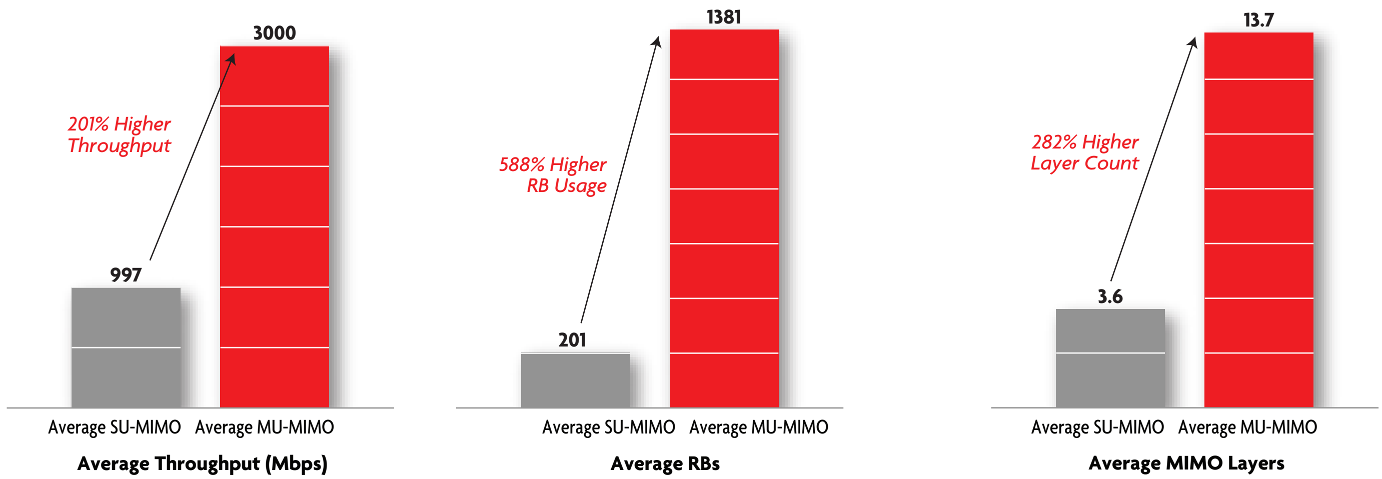
	RSRP (dBm)	SINR (dB)	Cell Site Distance (m)	Angle of Arrival (°)
UE #1	-63.0	25.3	42	210
UE #2	-69.8	35.2	341	229
UE #3	-73.3	27.5	427	213
UE #4	-73.2	23.2	81	268
UE #5	-67.9	25.8	187	274
UE #6	-70.2	31.2	114	256
UE #7	-71.7	26.9	70	229
UE #8	-72.2	27.2	178	242

Source: Signals Research Group

The MU-MIMO results, however, suggest otherwise, with a 201% increase in total throughput compared with the SU-MIMO base case results. Very high reuse of RBs (588% increase in RBs) and a high number of MIMO layers (13.7 MIMO layers on average) helps explain the high gain in total sector throughput.

Total sector throughput due to MU-MIMO increased by over 200%, compared with SU-MIMO, despite close angular separation and smartphones placed both near and far from the cell site.

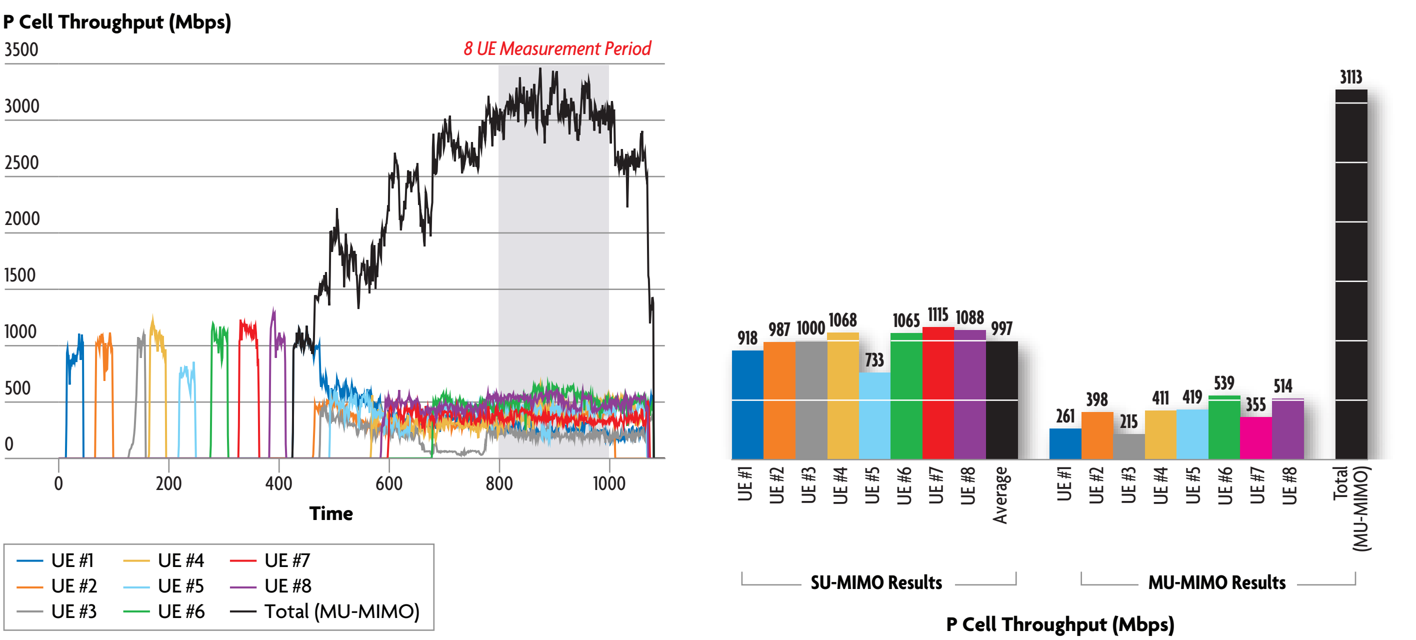
Figure 14. Summary of Results



Source: Signals Research Group

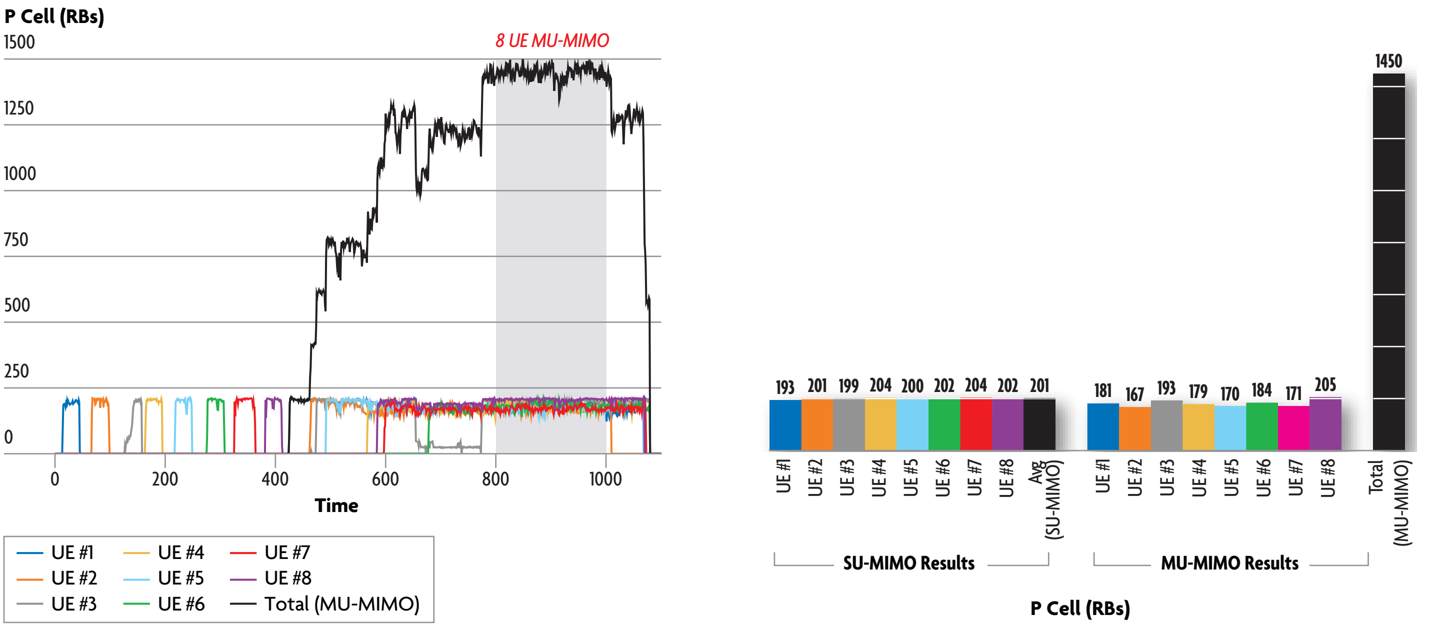
The next several figures help explain the strong gains. Each figure includes the SU-MIMO test results in the first ~400 seconds of the test, followed by the MU-MIMO test results. For the purpose of calculating the average MU-MIMO results, we included the period between 800 and 1,000 seconds when all eight smartphones were actively receiving data.

Figure 15. SU-MIMO and MU-MIMO Throughput



Source: Signals Research Group

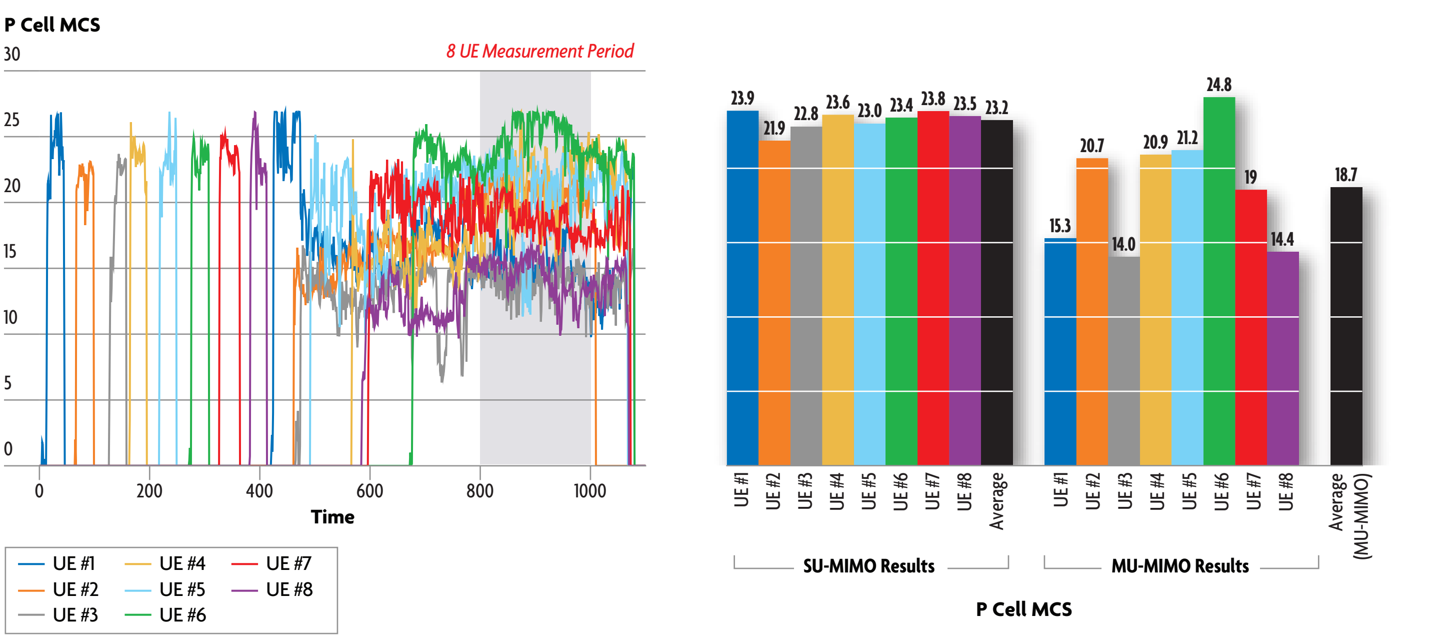
Figure 16. SU-MIMO and MU-MIMO RB Allocations



Source: Signals Research Group

The figures show how network performance (throughput, RBs, MIMO layers) increased as each smartphone started its data transfer. Note, for example, how the Total (MU-MIMO) downlink throughput in Figure 15 starts to increase at ~425 seconds and that the throughput continued to increase until all eight smartphones were receiving data. A similar phenomenon is evident with the RB allocations (Figure 16) and MIMO layers (Figure 18). MCS (Figure 17) allocations are unique to each smartphone and the notion of MCS sharing doesn't exist so there wasn't an associated increase in MCS as more phones started their data transfers.

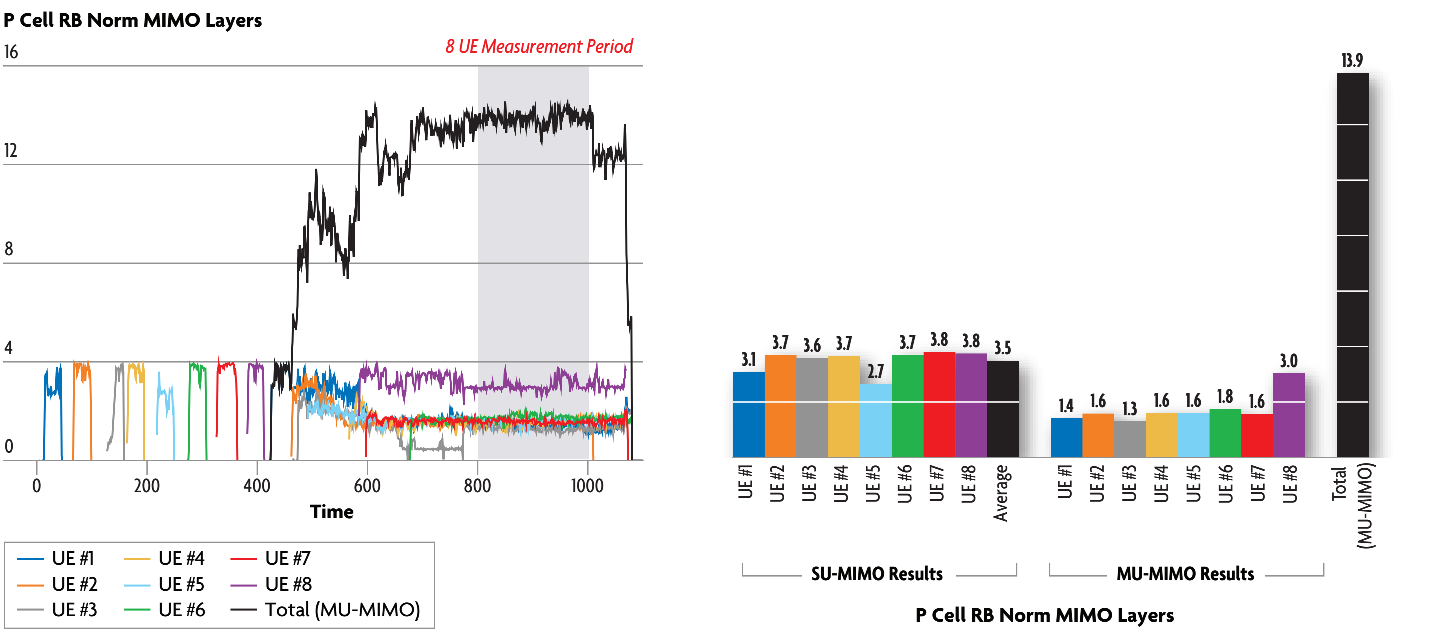
Figure 17. SU-MIMO and MU-MIMO MCS Allocations



Source: Signals Research Group

In this test, it is evident UE #3 wasn't performing as well as the other smartphones in both the SU-MIMO and MU-MIMO portions of the test. To provide a fair comparison of results, we excluded the slow ramp in the UE #3 SU-MIMO performance when calculating the average values. It wasn't practical to adjust its MU-MIMO performance, so we left those results unchanged. The net effect is the average MU-MIMO gains shown in Figure 14 slightly understate the potential MU-MIMO performance if the smartphone had been performing as expected.

Figure 18. SU-MIMO and MU-MIMO Layer Counts



Source: Signals Research Group

Downlink MU-MIMO test scenarios in the appendix include tests with four smartphones and eight smartphones and their comparative SU-MIMO results. We include a few tests from a different cell sector, which covered a nearby neighborhood that could easily be covered by the cell site with a FWA use case. The capacity gains due to MU-MIMO in these tests were generally in the low triple digits on a percentage base. We also include two tests in which one of the smartphones moved around the sector in a test vehicle, thereby showing the impact of mobility on MU-MIMO performance. Generally, with higher vehicular speeds, MU-MIMO didn't perform as well due to the nature of SRS-based beamforming. However, the remaining [stationary] phones continued to pair with each other, resulting in double and triple digit capacity gains.

As part of the mobility tests, we frequently stopped the test vehicle along the route to capture MU-MIMO performance from a new stationary test location that was much further away from the cell site. The average network capacity with a smartphone at these test spots, combined with the seven remaining phones, was an impressive 2.7 Gbps, equating to a 170% capacity gain relative to SU-MIMO. Lastly, there are results for one test scenario involving four smartphones downloading data and two smartphones uploading data. The results from this test show nearly 100% capacity gains in both directions, despite two of the smartphones being located several hundred meters from the cell site.

The appendix includes a test scenario involving four smartphones downloading data and two smartphones uploading data, with results showing nearly 100% gains in both directions.

Uplink MU-MIMO is very resilient while delivering high capacity gains to meet the growth of uplink data traffic

We include results for two uplink MU-MIMO test scenarios in this section and some additional uplink MU-MIMO results in the appendix. Like the downlink tests, we first tested each smartphone by itself to determine the average/expected performance with SU-MIMO. We then tested four smartphones together for the uplink MU-MIMO scenario. Figure 19 shows the locations of the four smartphones for the first uplink test scenario along with important RF characteristics.

Figure 19. Test Case 1 Mobile Phone Locations and Key RF Metrics

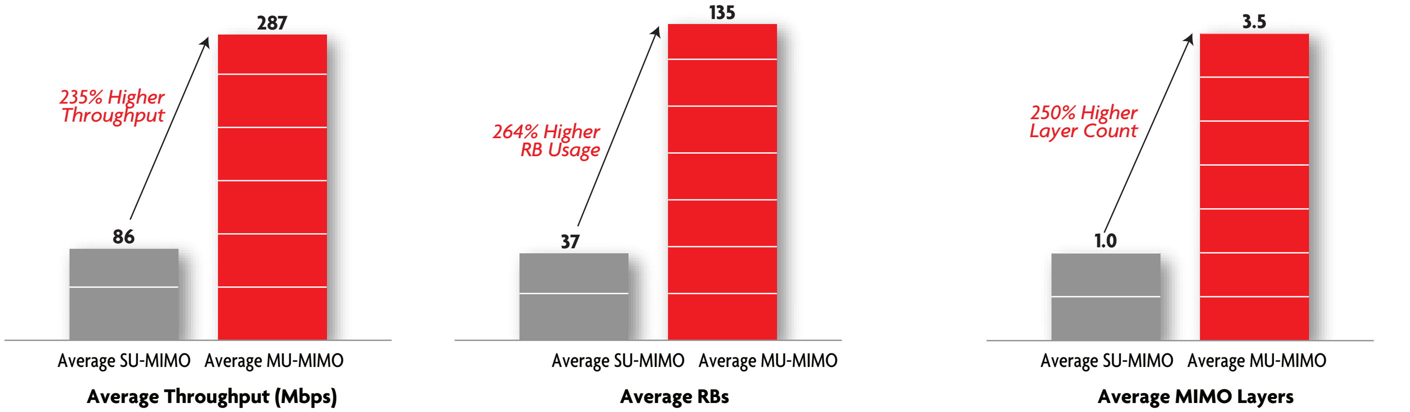
	RSRP (dBm)	SINR (dB)	Cell Site Distance (m)	Angle of Arrival (°)
UE #1	-69.7	28.1	95	276
UE #2	-69.5	26.9	99	260
UE #3	-68.9	30.8	98	239
UE #4	-67.4	24.5	66	223

Source: Signals Research Group

As we did with the downlink MU-MIMO results, we first show summary information about the benefits of uplink MU-MIMO before providing more detailed information and analysis to support our findings. As shown in Figure 20, uplink MU-MIMO increased the uplink capacity by 235% over the SU-MIMO base case, thanks to a high reuse of RBs (264% higher RB use) and an average of nearly four MIMO layers (3.5 layers, representing an increase of 250% from the SU-MIMO scenario). We point out that today's smartphones are limited to a single 5G uplink MIMO layer when operating in NSA mode since there also needs to be an LTE layer.

Uplink MU-MIMO increased the uplink capacity by 235% over the SU-MIMO base case.

Figure 20. Summary of Results

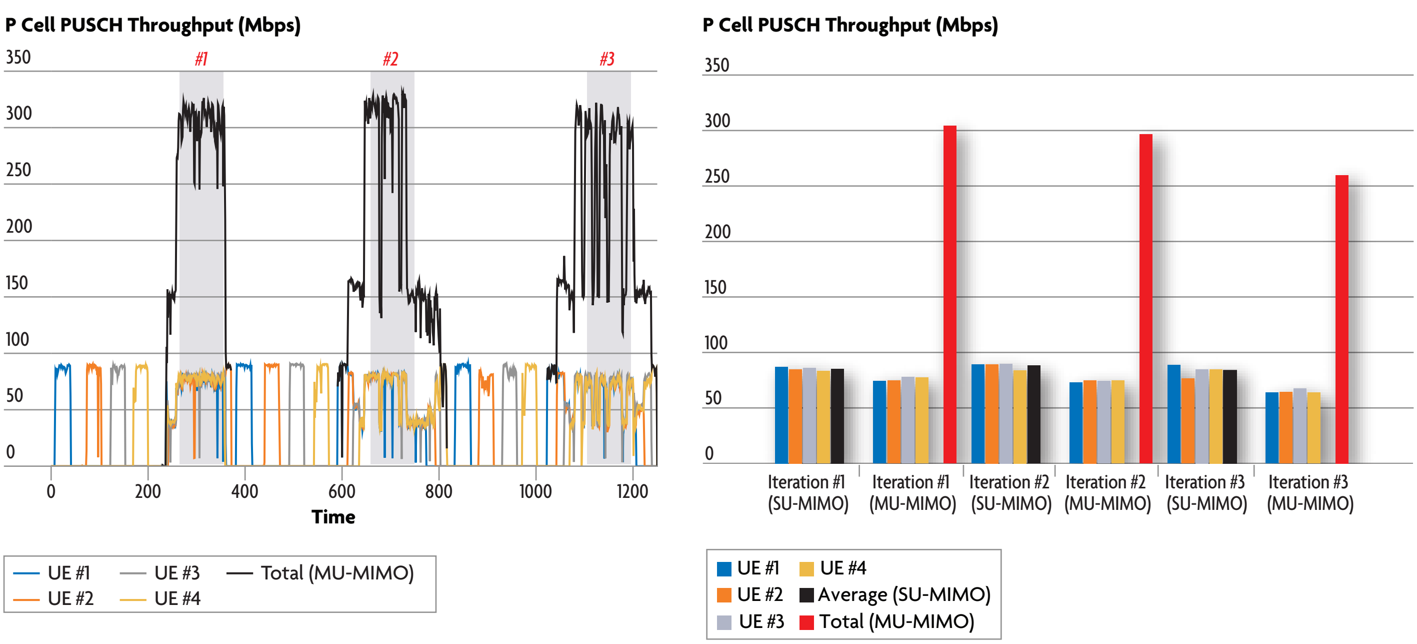


Source: Signals Research Group

We repeated this test three times with consistent results for both SU-MIMO and MU-MIMO, as documented in the following figures. When testing each smartphone by itself, the average uplink throughput was between 84 Mbps and 88 Mbps (average = 86 Mbps), jumping to a total uplink throughput between 260 Mbps and 304 Mbps (average = 287 Mbps). With 20% of the bandwidth allocated to the uplink direction, the implied spectral efficiency was 14.4 bps/Hz.

The implied uplink spectral efficiency with MU-MIMO was 14.4 bps/Hz.

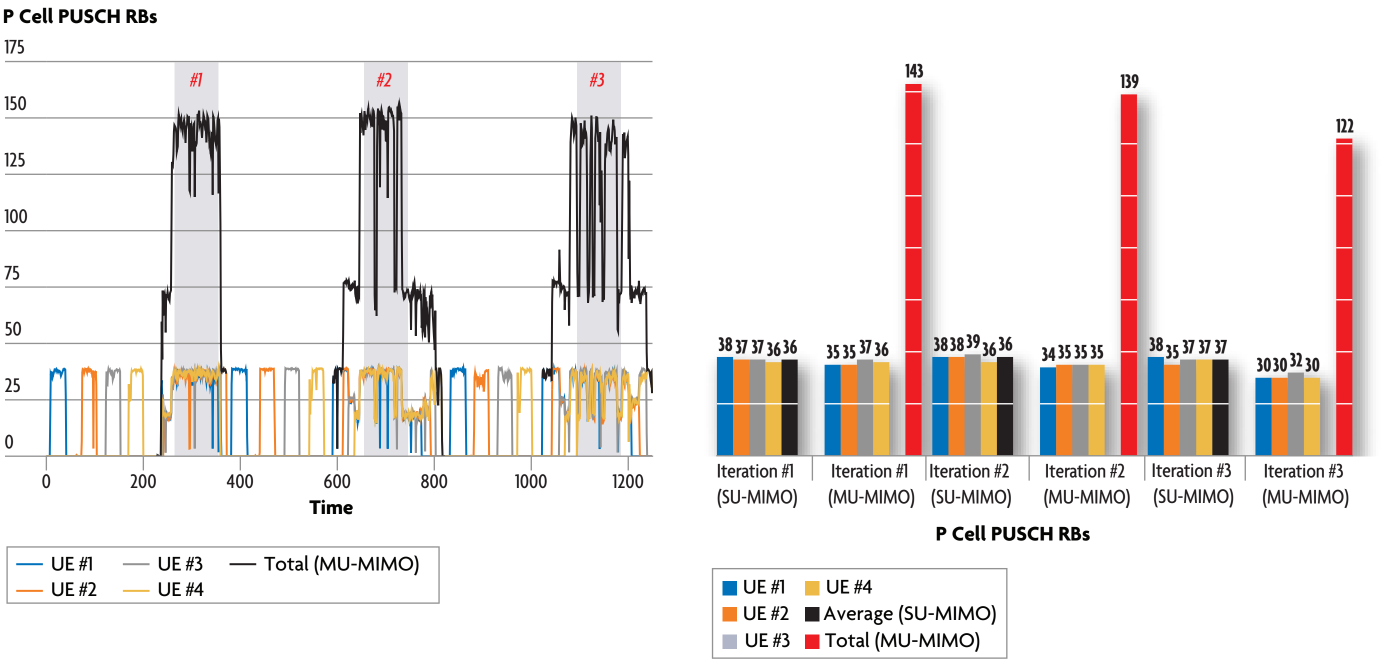
Figure 21. SU-MIMO and MU-MIMO Throughput



Source: Signals Research Group

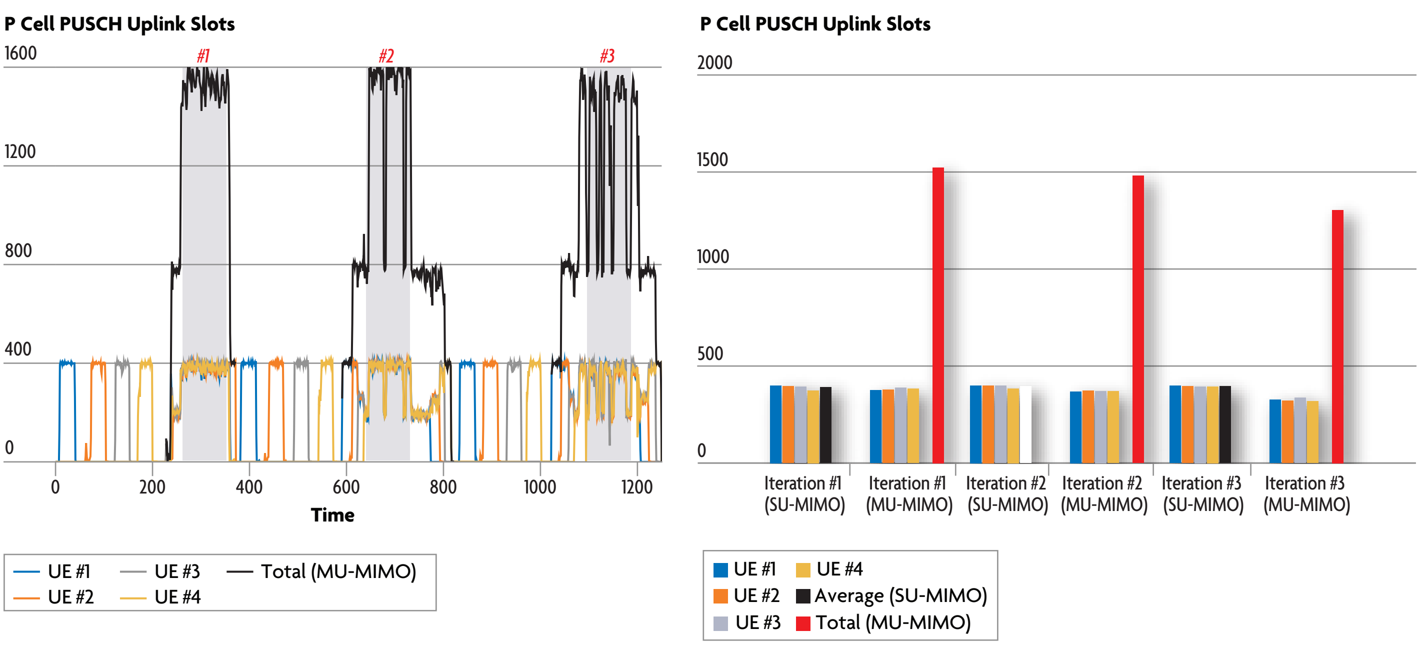
Looking at the underlying performance metrics, there were also consistent results between the three tests for resource block allocations (Figure 22) slot allocations (Figure 23), MCS values (Figure 24), and

Figure 22. SU-MIMO and MU-MIMO RB Allocations



Source: Signals Research Group

Figure 23. SU-MIMO and MU-MIMO Time Slot Allocations



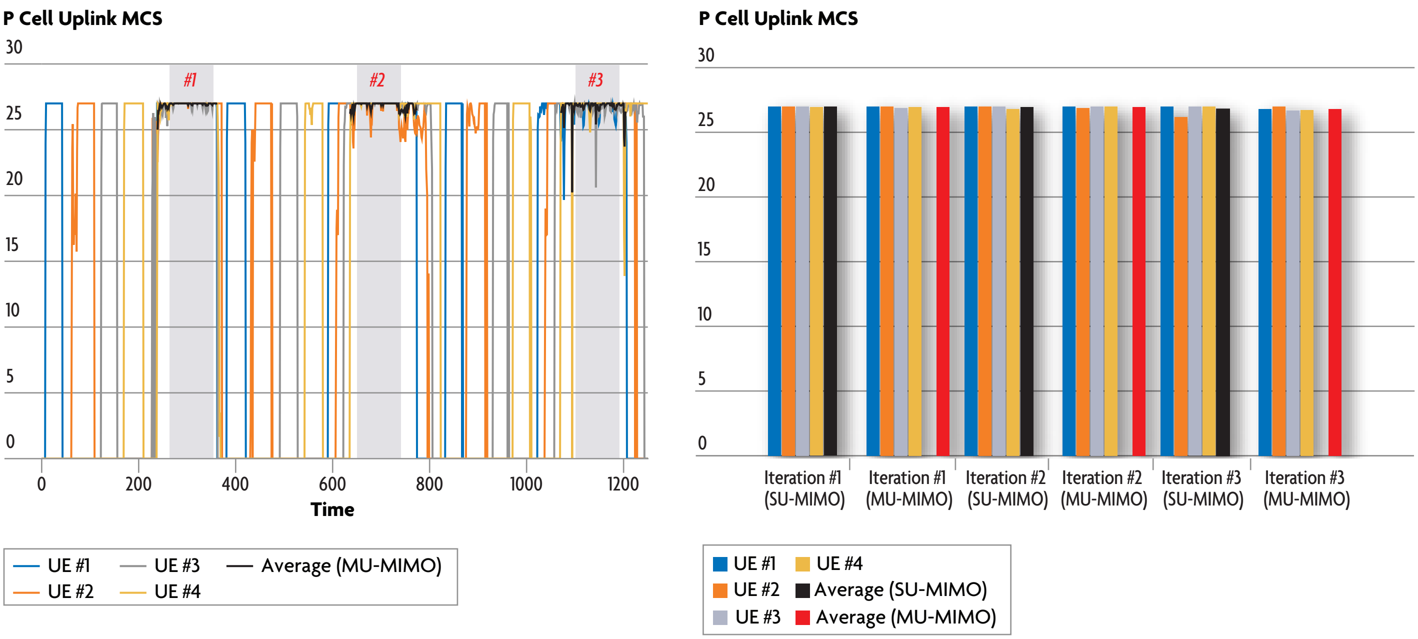
Source: Signals Research Group

MIMO layers (Figure 25).

In all SU-MIMO and MU-MIMO tests, the uplink MCS values were almost consistently at the highest possible value, suggesting that MU-MIMO pairing had very little impact on the interference in the uplink direction. The MU-MIMO results in the RB, time slot, and MIMO layer figures closely resemble each other since there are inherent dependencies between the three metrics. Resource block alloca-

MU-MIMO pairing had very little impact on the interference in the uplink direction.

Figure 24. SU-MIMO and MU-MIMO MCS Allocations

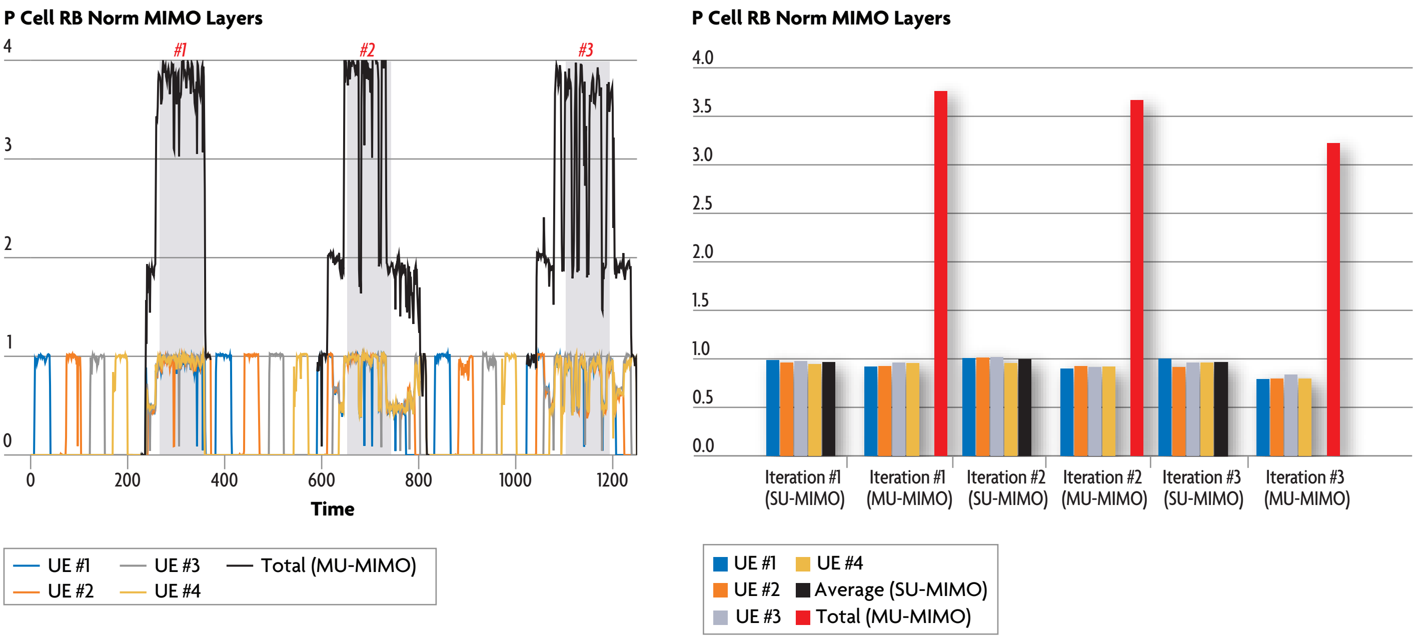


Source: Signals Research Group

tions coincide with the time slots where the RBs are assigned. Likewise, each smartphone's MIMO layer count depends on its RB allocation.

As explained in the test methodology section, we normalized the MIMO layers to the RB allocations. For example, with our approach the uplink MIMO layer count would only be 1 layer if the smartphone was using all uplink RBs. If a smartphone was only using 50% of the RBs then its uplink MIMO layer count would be 0.5 (50% of RBs x 1 Layer = 0.5 Layers).

Figure 25. SU-MIMO and MU-MIMO Layer Allocations



Source: Signals Research Group

With the second uplink MU-MIMO test shown in this section, we positioned two smartphones much further away from the cell site, as shown in Figure 26.

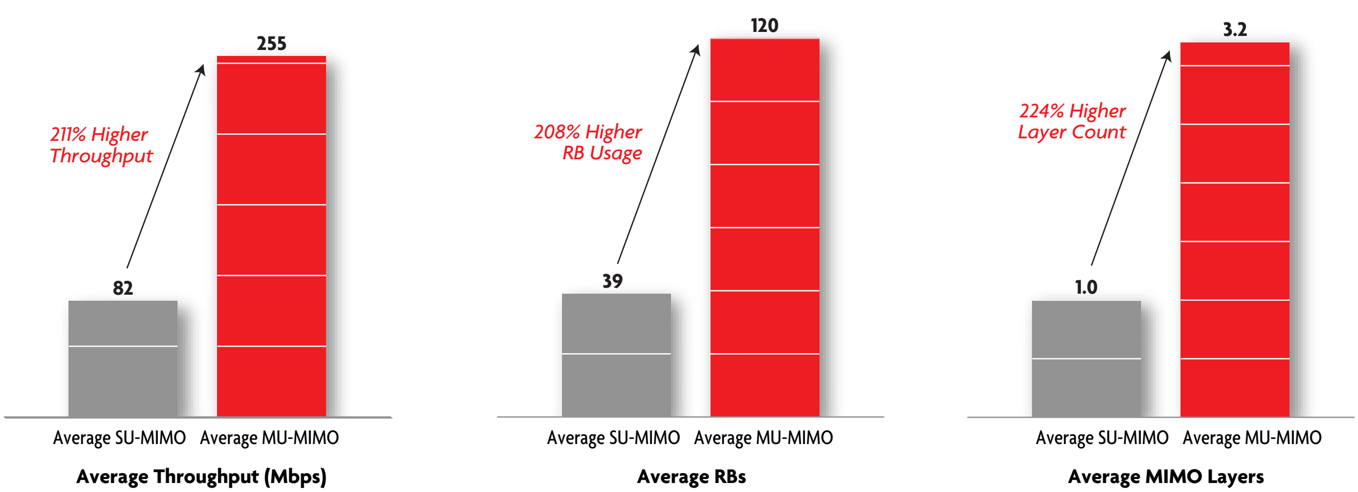
Figure 26. Test Case 14 Mobile Phone Locations and Key RF Metrics

	RSRP (dBm)	SINR (dB)	Cell Site Distance (m)	Angle of Arrival (°)
UE #1	-63.2	24.3	41	210
UE #2	-71.7	24.7	340	229
UE #3	-67.8	24.6	340	215
UE #4	-67.7	25.5	102	268

Source: Signals Research Group

Nonetheless, the performance gains due to uplink MU-MIMO were quite strong with a 211% increase in uplink throughput compared with the SU-MIMO base case scenario. The strong results were due to a combination of high RB reuse (208% higher RB usage) and layer count (224% improvement), along with consistent MCS allocations between SU-MIMO and MU-MIMO.

Figure 27. Summary of Results

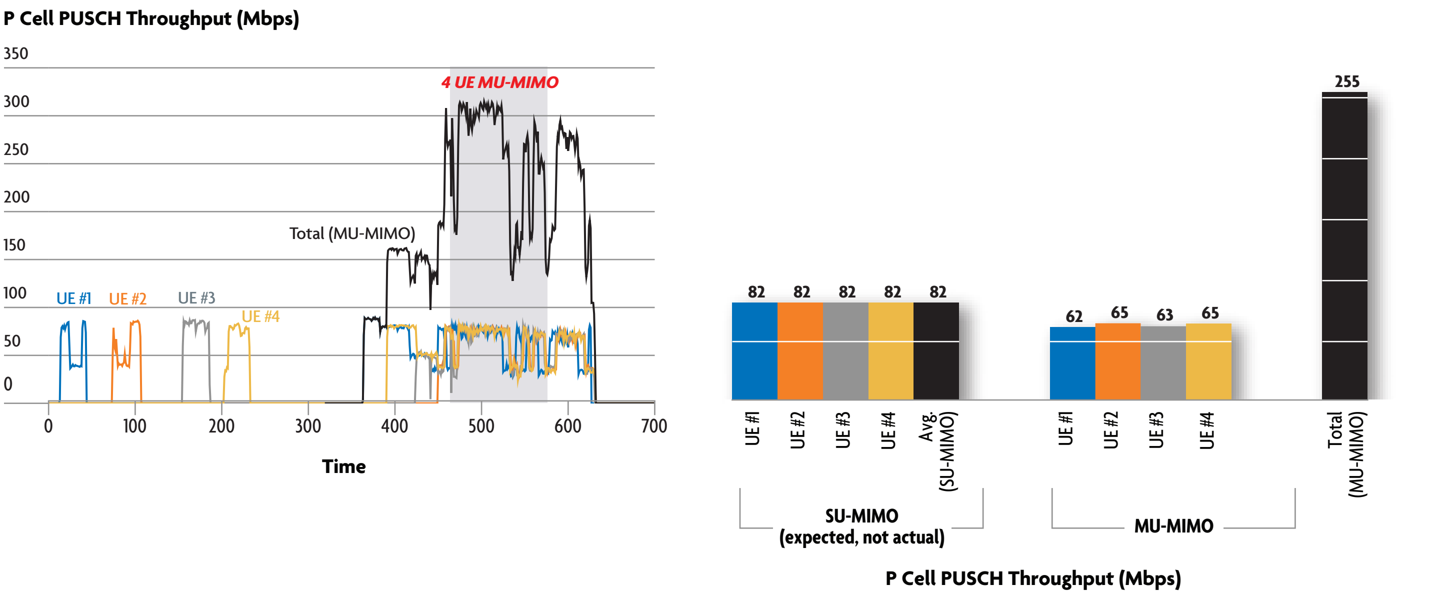


Source: Signals Research Group

The detailed results in the following figures show how the smartphones paired with each other as well as some instances when the pairing was less successful. During the SU-MIMO portions of these tests, the UE behavior, especially for UE #1 and UE #2, was not consistent with our expectations for SU-MIMO. The behavior we observed was likely caused by extraneous network traffic on the commercial network, which limited the network resources being assigned to our test phones.

For this reason, we elected to use average PUSCH throughput, RB allocations and MIMO layers for the SU-MIMO results which were more consistent with expectations than what we recorded in this test. This action resulted in average values shown in the bar charts in the next two figures, as well as in Figure 31, which are higher than what we measured with each UE, in particular UE #1 and UE #2. We note the extraneous network traffic could have also been occurring during the MU-MIMO portion of the test, but we did not make any adjustments to the results we recorded. The impact of this decision results in more conservative SU-MIMO results than what we actually documented in our tests, meaning we are showing uplink MU-MIMO gains which are lower than what we observed in these tests.

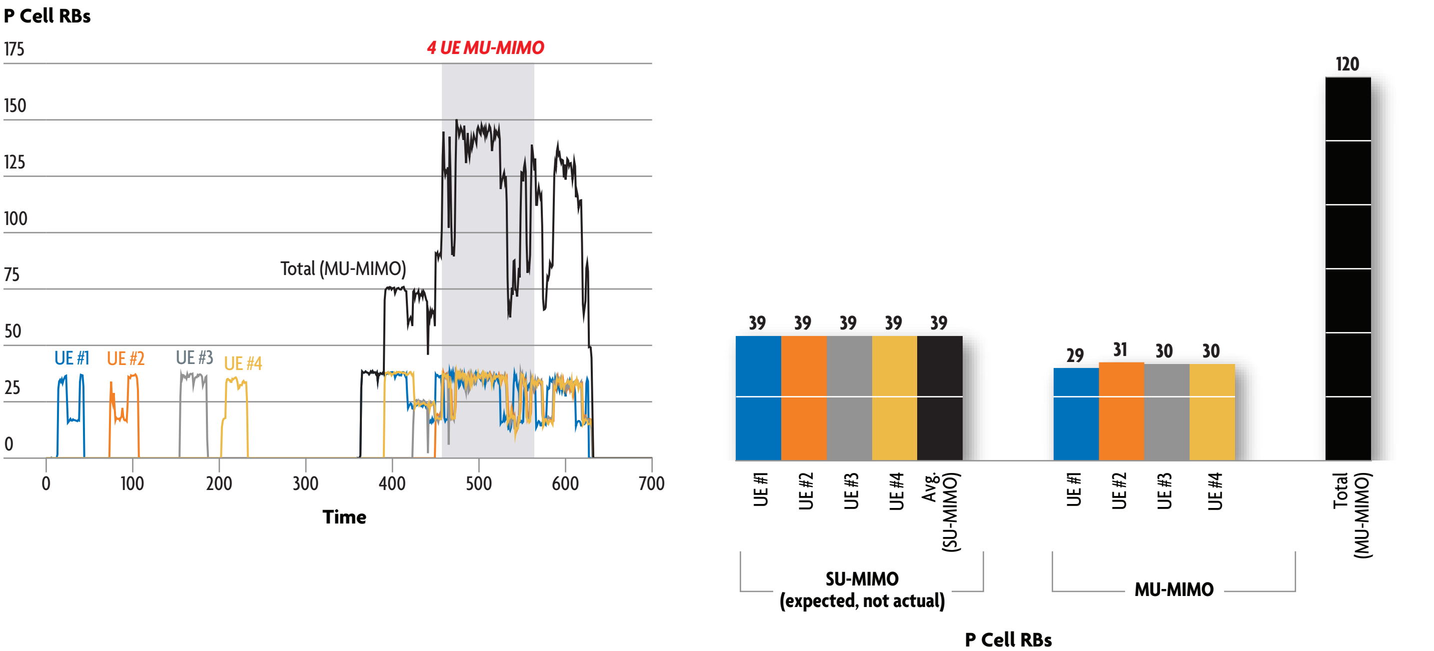
Figure 28. SU-MIMO and MU-MIMO Throughput



Source: Signals Research Group

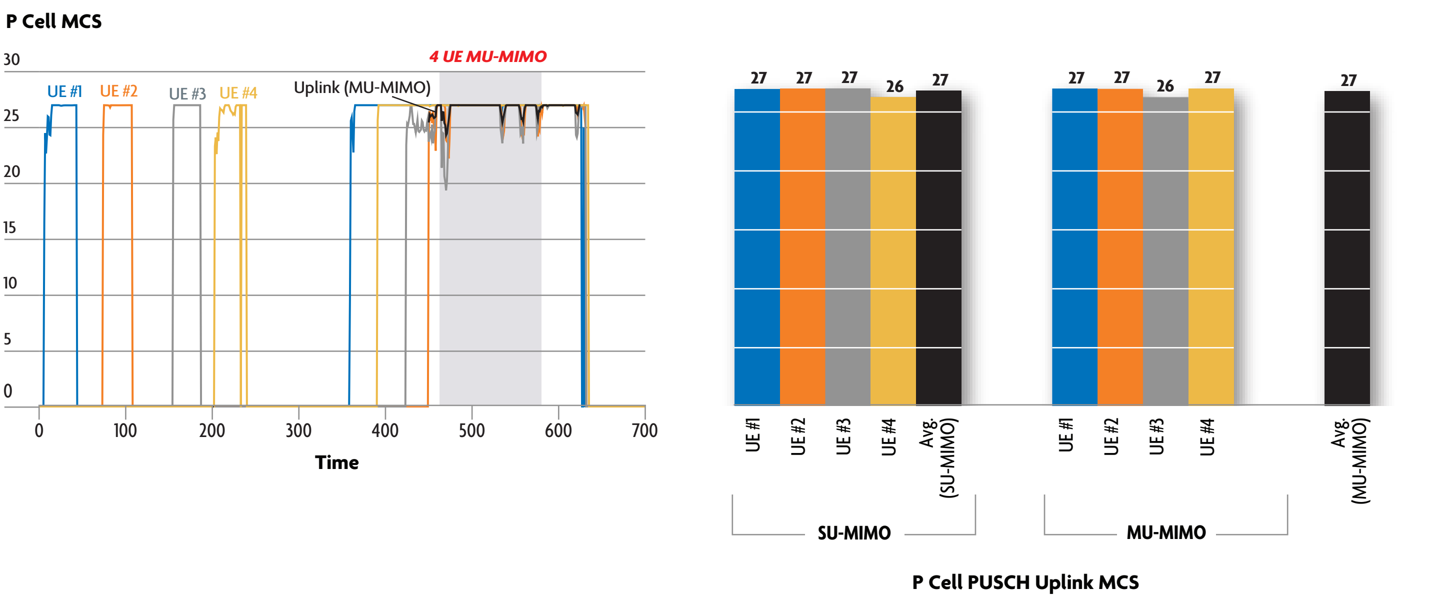
Notably, UE #1 went in and out of RB pairing with the other three phones between ~525 and ~550 seconds (Figure 29) while the MCS allocations remained relatively constant, albeit with some very brief dips that coincided in time for all four smartphones (Figure 30).

Figure 29. SU-MIMO and MU-MIMO RB Allocations



Source: Signals Research Group

Figure 30. SU-MIMO and MU-MIMO MCS Allocations

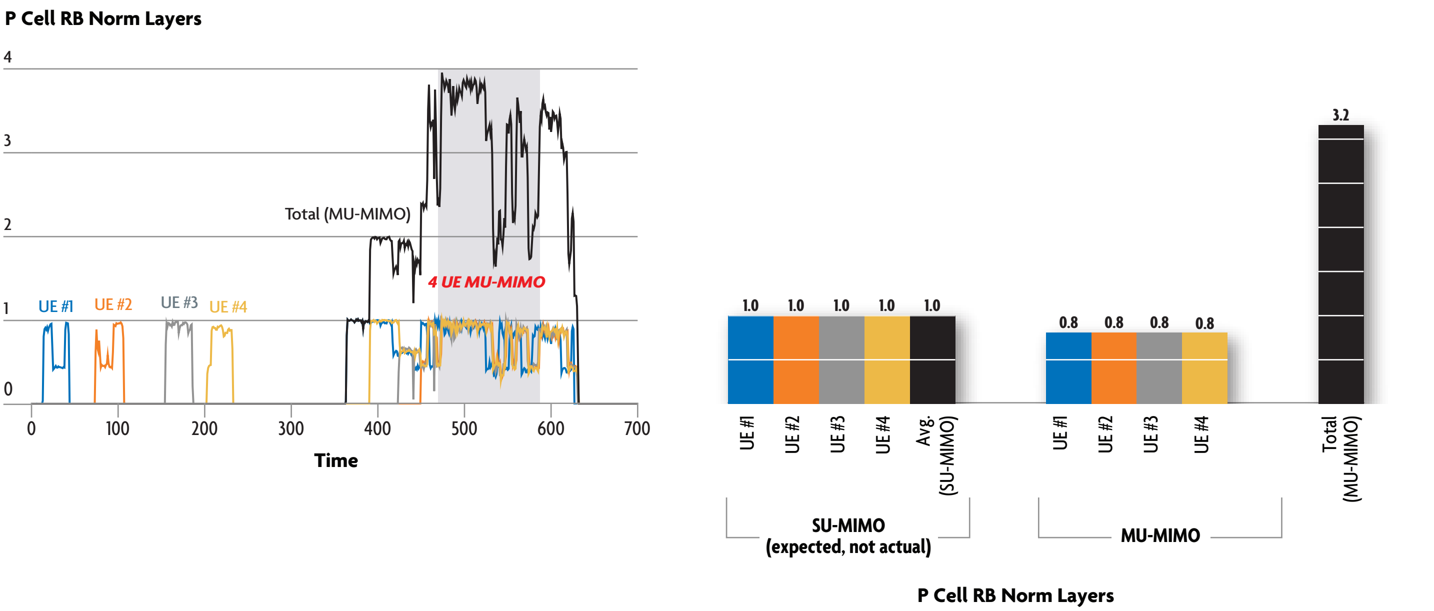


Source: Signals Research Group

Looking at the location of UE #1 in Figure 26, it is evident that this smartphone was positioned almost in line with UE #3 and UE #2, while UE #2, UE #3, and UE #4 had greater horizontal separation with each other. Our takeaway is that even with tight separation, uplink MU-MIMO pairing still works and when a smartphone's location causes pairing issues with the other smartphones, there is still nothing preventing the other smartphones from pairing with each other while the "troublesome" smartphone is scheduled separately. Put another way, even when there wasn't pairing between UE #1 and the other three phones, there was still more than a 2x increase in uplink throughput relative to the SU-MIMO base case.

Even with tight separation, uplink MU-MIMO pairing still works and if one smartphone is no longer able to pair, it doesn't prevent the other smartphones from pairing with each other.

Figure 31. SU-MIMO and MU-MIMO Layer Allocations



Source: Signals Research Group

Test Methodology

In our 5G benchmark studies, we leverage test and measurement equipment from our trusted partners to conduct rigorous analysis of device and network performance. We capture chipset diagnostic messages from the modem in the smartphone which provides 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 Samsung Galaxy S23 smartphone.

Given the logistical challenges of testing from up to eight different locations, we leveraged Samsung engineers to help us collect the data. SRG managed the testing process, including the selection of the test cases and the location of the smartphones for each test. Since it wasn't possible to enable and disable MU-MIMO functionality in a commercial network, we took an average of each smartphone's performance when transferring data by itself to determine SU-MIMO results, which we then used to compare with the MU-MIMO results. Since we were testing in a commercial network, we can't rule out other data traffic impacting the results we show in this report. If anything, the extraneous network traffic likely resulted in our findings underestimating the true capabilities of MU-MIMO.

When testing MU-MIMO, we started the data transfer on each phone in a serial fashion until all smartphones were transferring data. This approach makes it possible to show on MU-MIMO increased performance (throughput, RBs, MIMO layers) compared with SU-MIMO and a single smartphone transferring data. We then selected the time period when all smartphones were transferring data to analyze MU-MIMO performance and used these results to compare with the SU-MIMO base case performance. We used iPerf to generate the full buffer downlink/uplink data transfers.

We've worked with Accuver Americas since we did our first LTE benchmark study in 2009. For this study, we used the company's XCAL-M drive test tool to capture the diagnostic messages from the 5G modem in the smartphone. In addition to capturing the diagnostic messages, we captured the GPS coordinates so that we knew the location of each test phone, plus the GPS time stamps helped us align the results from each log file.

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

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. For purposes of our analysis, we included the basic RF parameters (RSRP and SINR), as well as the most pertinent performance parameters for analyzing MU-MIMO. These parameters included PDSCH/PUSCH throughput, resource block (RB) allocations, MIMO layers, and MCS allocations. Almost all of our analysis was specific to the Band n77 primary cell (P Cell) although we did capture performance parameters for the Band n77 secondary cell (S Cell) and the LTE anchor band.

One nuance to our data analysis is that we needed to normalize each smartphone's reported number of MIMO layers to its RB allocations. The chipset reporting mechanism provides each phone's MIMO layer count for the RBs the network allocated to the phone. With SU-MIMO, multiple smartphones can use four MIMO layers, but the network distributes the RBs among all active phones. Therefore, if we simply added the MIMO layer counts for all phones in the test, we could end up with an obviously erroneous number of total MIMO layers, or 32 MIMO layers (8 phones x 4 layers). Therefore, we calculated what we refer to as the RB normalized MIMO Layer count, which is defined as the number of reported MIMO Layers multiplied by the ratio of RBs the phone used relative to the total RBs available.

RB Norm MIMO Layers = Reported MIMO Layers × (Allocated RBs ÷ Total RBs)

As an example, if a smartphone reported four MIMO layers and the network allocated it 105 RBs out of the maximum 210 RBs available in the network then its RB normalized MIMO layer count would be two layers, even though the phone was actually using four MIMO layers, albeit with only half the RBs. Achieving sixteen RB normalized MIMO layers with the eight phones we used in our tests would require all eight phones to use two MIMO layers and all 210 RBs. Other permutations are also possible, but it would still require sixteen MIMO layers used across all available RBs (e.g., sixteen layers occurring within the same time slot).

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 37 benchmark studies in Signals Ahead pertaining to the next generation technology through the end of 2023. 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. s part of these studies, we've evaluated MU-MIMO on a few occasions. However, our testing was limited with respect to the number of smartphones we used in our tests, so we never had the opportunity to push the boundaries of MU-MIMO performance with sixteen possible downlink layers. Additionally, until we did this study, we never specifically evaluated uplink MU-MIMO performance, so this study marks the first time that we have had the chance to do so.

Our philosophy in doing benchmark studies is that we are even keeled, data-driven, and as objective as possible. We present the study's findings with as much performance data and analysis as possible and then let the results speak for themselves.

Appendix – even more downlink and uplink MU-MIMO results

In this appendix, we included results from additional test cases that we conducted as part of this benchmark study. Table 1 identifies all valid test cases that we conducted as part of this study along with a summary of the results. Those test cases that are shaded were discussed in the earlier section. Since we have already explained how we collected and analyzed the data, and the format of the figures in the appendix mirrors what we provided earlier in this paper, we are not providing as much commentary in the appendix. However, we believe it is still important to document the breadth of this study along with the range of results we obtained. Since some of these test cases were similar to each other (e.g., 4 UEs versus 8 UEs) and with comparable results, we are not showing detailed results for all test cases, although the capacity gains are identified in the table below.

Table 1. Summary of Test Cases

Test Case Number	Description	Summary of Results
TC1	4 UE uplink with phones positioned near the cell site	More than 230% higher uplink throughput versus SU-MIMO
TC2	4 UE uplink with 1 UE in vehicle driven around the sector; periodic stopping at several points	Average capacity gain of nearly 150% versus SU-MIMO
TC3	4 UEs positioned adjacent to each other	MU-MIMO performance was comparable to SU-MIMO
TC6	8 UE downlink with phones positioned near the cell site	220% higher downlink throughput versus SU-MIMO
TC7	4 UE downlink with phones positioned near the cell site	Just over 110% higher downlink throughput versus SU-MIMO
TC8	8 UEs in residential neighborhood, positioned in front of homes and relatively close to the cell site (FWA use case)	Nearly 120% higher downlink throughput versus SU-MIMO
TC11	4 UEs in residential neighborhood, positioned in front of homes and relatively close to the cell site (FWA use case)	Nearly 120% higher downlink throughput versus SU-MIMO
TC12	Repeat of TC11 with 1 UE in vehicle driven around the neighborhood; periodic stopping at several points	Average capacity gain of over 90% versus SU-MIMO
TC14	4 UE uplink, including 2 UEs located several hundred meters from the cell site	Just over 210% higher uplink throughput versus SU-MIMO
TC15	4 UE downlink, including 2 UEs located several hundred meters from the cell site	Average capacity gain close to 90% versus SU-MIMO
TC16	8 UE downlink, including 4 UEs located several hundred meters from the cell site	Just over 200% higher downlink throughput versus SU-MIMO
TC17	Repeat of TC16 with 1 UE in vehicle driven around the sector; periodic stopping at several points	Just over 170% higher downlink throughput versus SU-MIMO
TC18	4 UEs downloading data and 2 UEs transmitting data simultaneously; 3 UEs located several hundred meters from the cell site	Approaching 100% capacity gains in both the downlink and uplink directions

Source: Signals Research Group

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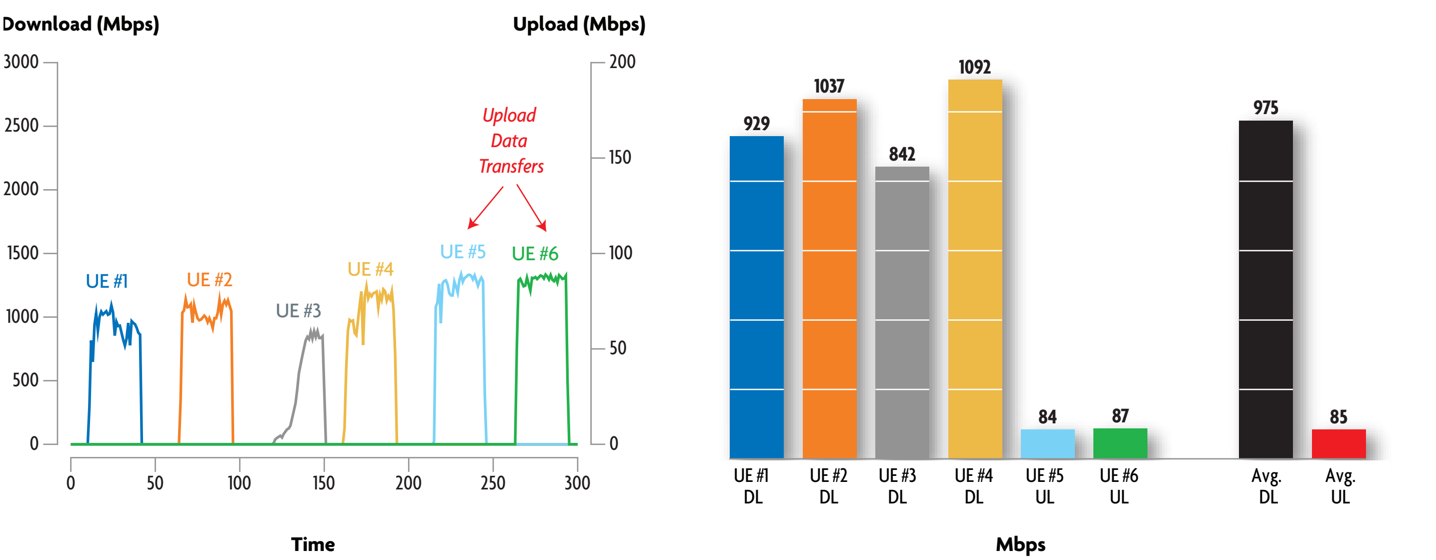
Test Case 18 involved four smartphones receiving data in the downlink direction and two smartphones transmitting data in the uplink direction. The next several figures highlight the results from this test. Of note, in the time series figures we plotted the downlink results along the primary Y axis and the uplink results along the secondary Y axis. The results show a near doubling of downlink and uplink throughput compared with the SU-MIMO test.

Figure 32. Test Case 18 Mobile Phone Locations and Key RF Metrics

	RSRP (dBm)	SINR (dB)	Cell Site Distance (m)	Angle of Arrival (°)
UE #1	-55.1	29.0	42	218
UE #2	-68.7	34.2	357	230
UE #3	-77.5	31.8	423	228
UE #4	-69.6	25.6	96	275
UE #5	-68.1	38.4	358	213
UE #6	-73.6	26.2	113	259

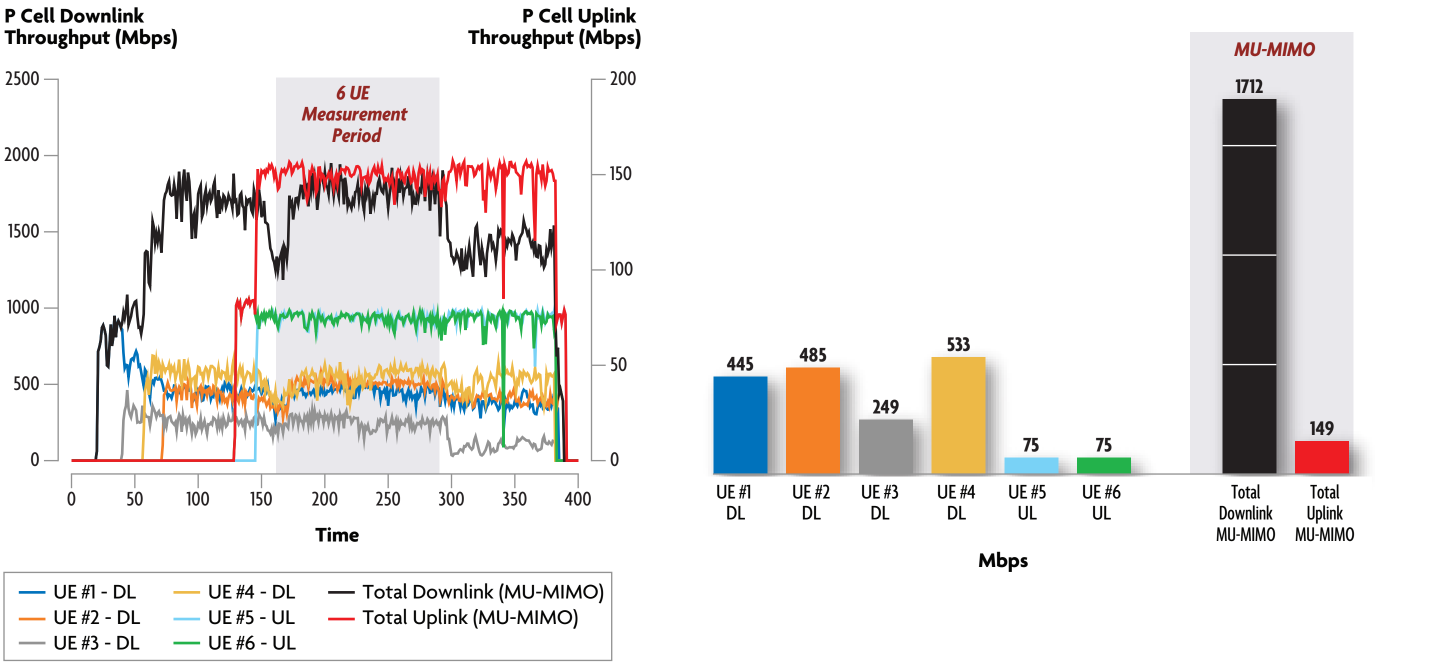
Source: Signals Research Group

Figure 33. Test Case 18 SU-MIMO Throughput



Source: Signals Research Group

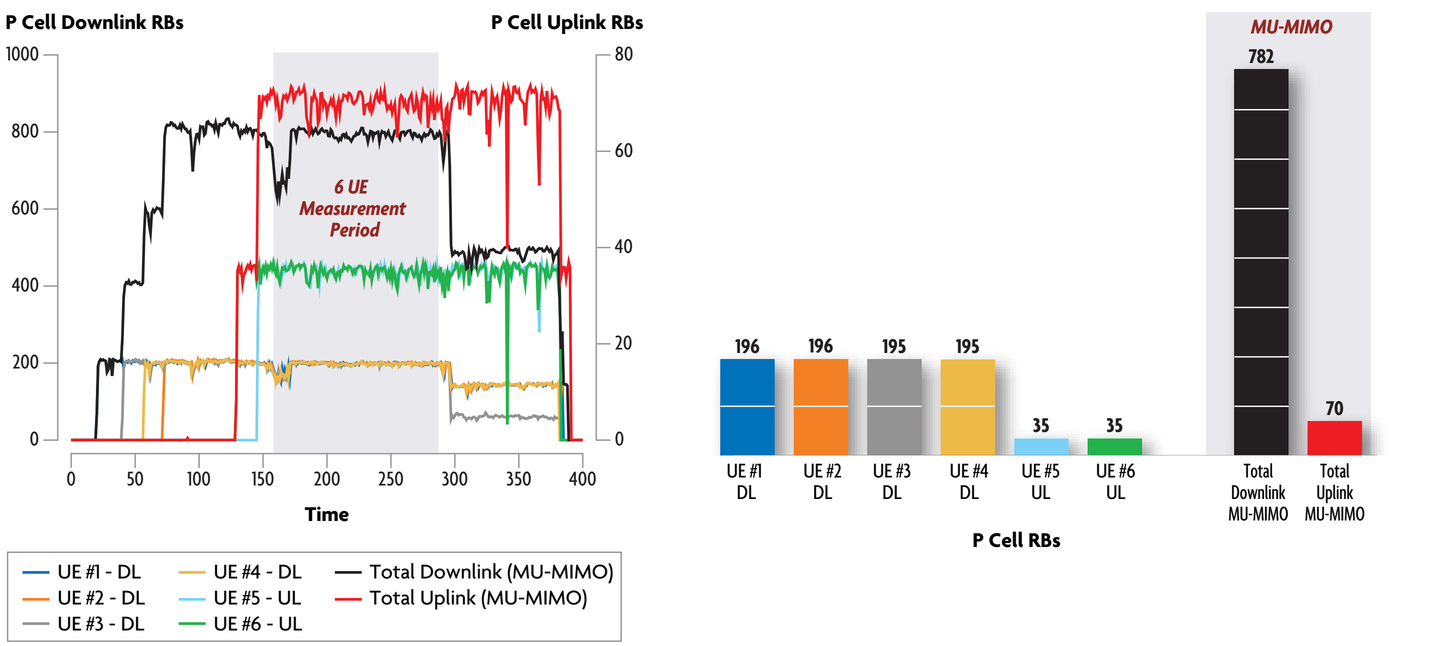
Figure 34. Test Case 18 MU-MIMO Throughput



Source: Signals Research Group

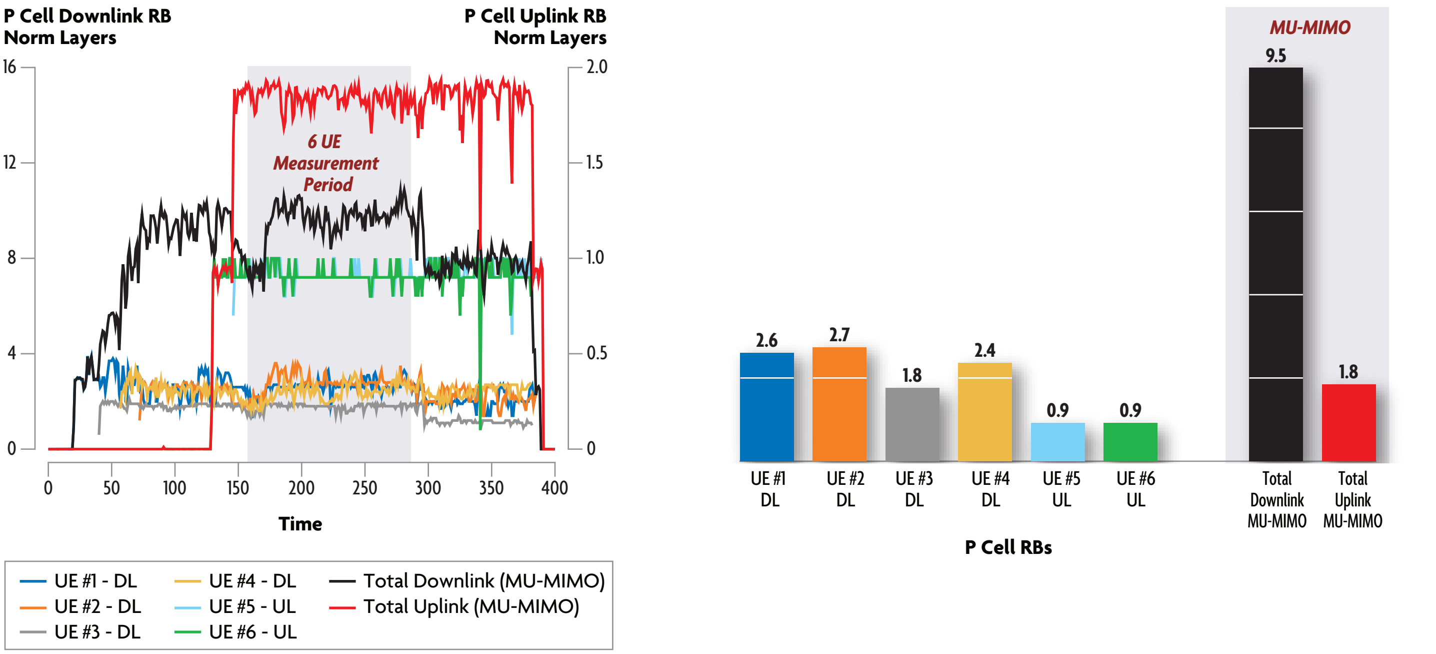
Since we've already quantified the maximum number of possible RBs and MIMO layers in the downlink and uplink direction with SU-MIMO, we are not including the SU-MIMO results for this test.

Figure 35. Test Case 18 Resource Block Allocations with MU-MIMO



Source: Signals Research Group

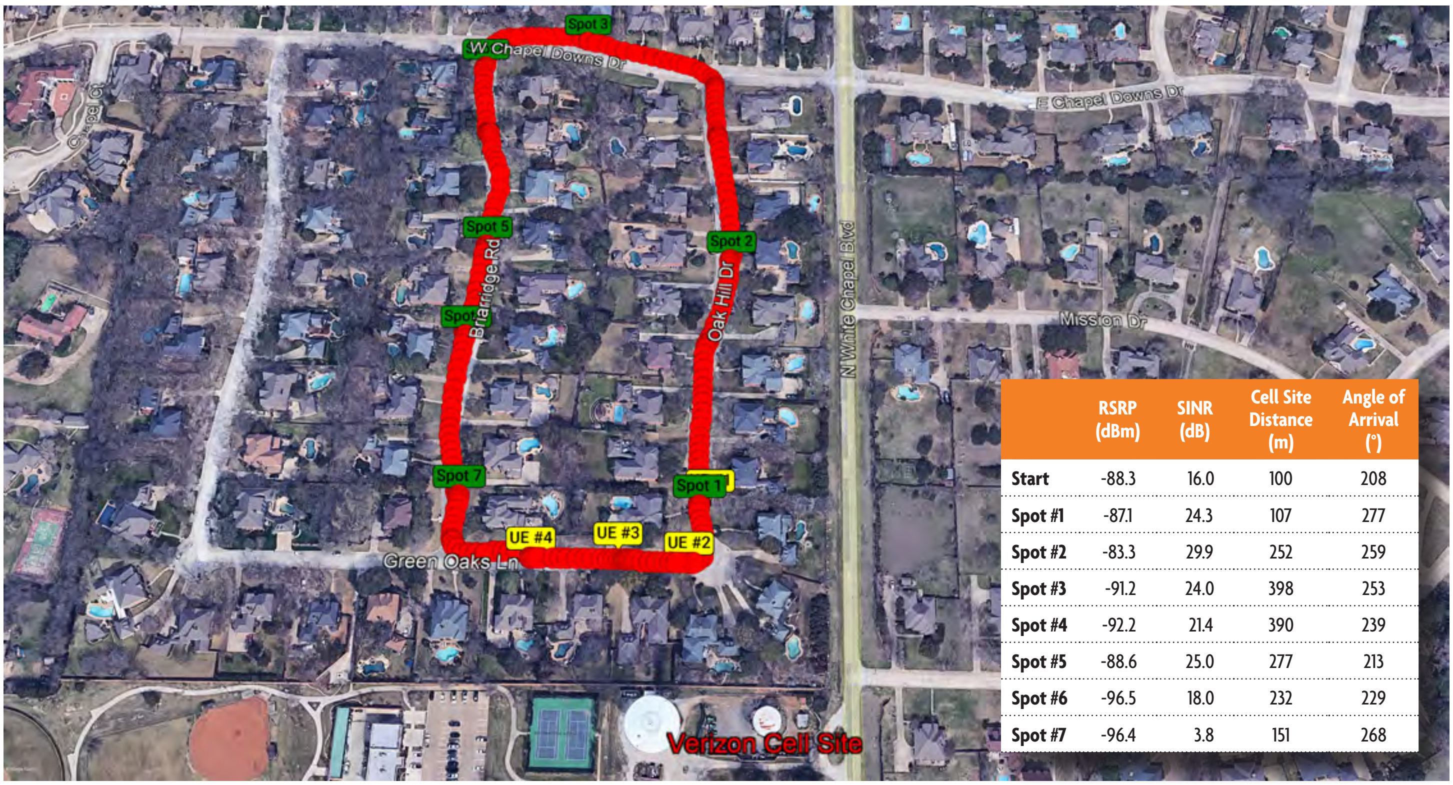
Figure 36. Test Case 18 MIMO Layers with MU-MIMO



Source: Signals Research Group

We conducted Test Case 8, Test Case 11, and Test Case 12 in the neighborhood to the north of the cell site. Test Case 12 was the most challenging of the three test cases and the most interesting since it involved one smartphone (UE #4) in a moving vehicle along with multiple stops along the drive route. Therefore, we are just highlighting the results for this test. Figure 37 shows the locations of the three stationary phones, the drive route we used, and the locations where we momentarily stopped while continuously testing MU-MIMO performance. In this figure, the spot showing the location of UE #4 indicates its initial position before starting the drive test.

Figure 37. Test Case 12 Mobile Phone Locations and Key RF Metrics

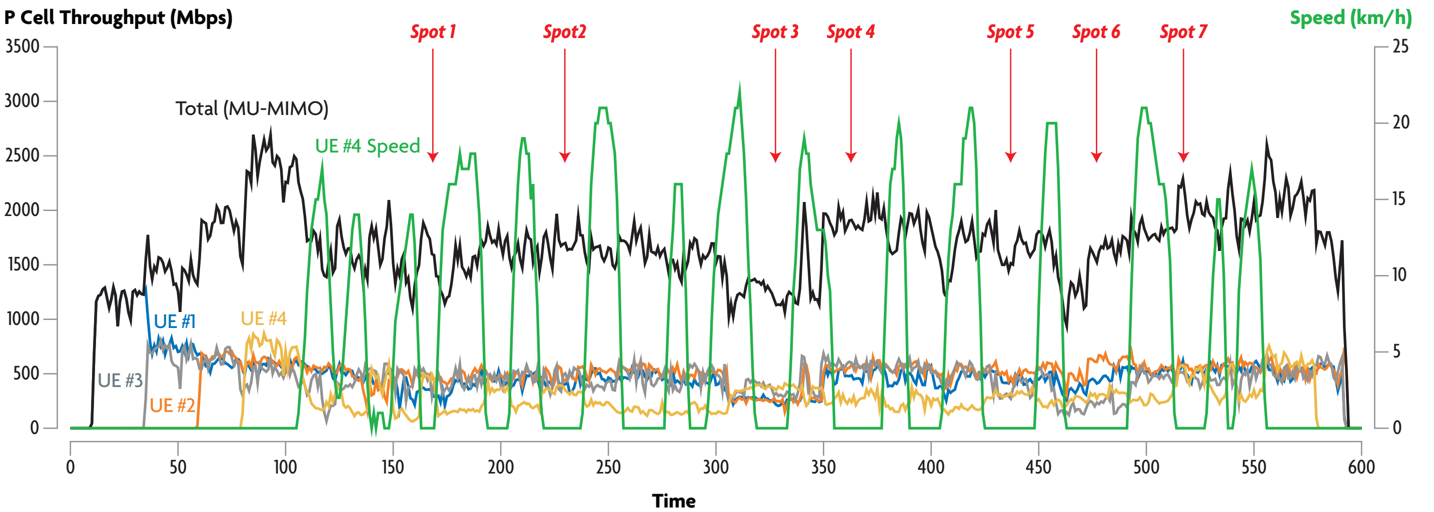


	RSRP (dBm)	SINR (dB)	Cell Site Distance (m)	Angle of Arrival (°)
Start	-88.3	16.0	100	208
Spot #1	-87.1	24.3	107	277
Spot #2	-83.3	29.9	252	259
Spot #3	-91.2	24.0	398	253
Spot #4	-92.2	21.4	390	239
Spot #5	-88.6	25.0	277	213
Spot #6	-96.5	18.0	232	229
Spot #7	-96.4	3.8	151	268

Source: Signals Research Group

Figure 38 shows the throughput for each smartphone as well as the total throughput during the drive test. The figure also plots the vehicular speed of UE #4 along the secondary Y axis.

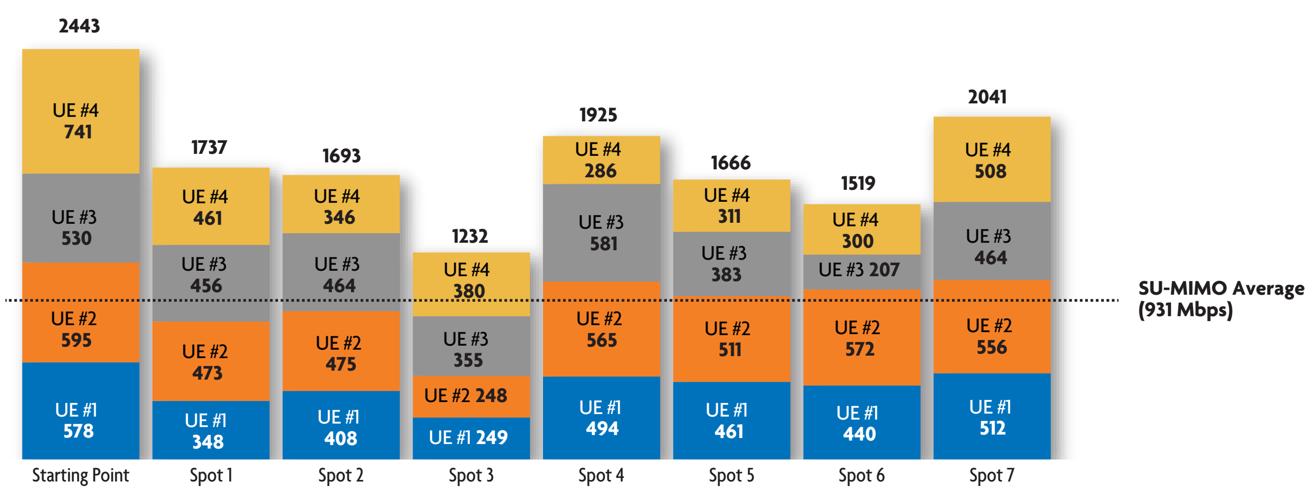
Figure 38. Test Case 12 Downlink Throughput with MU-MIMO



Source: Signals Research Group

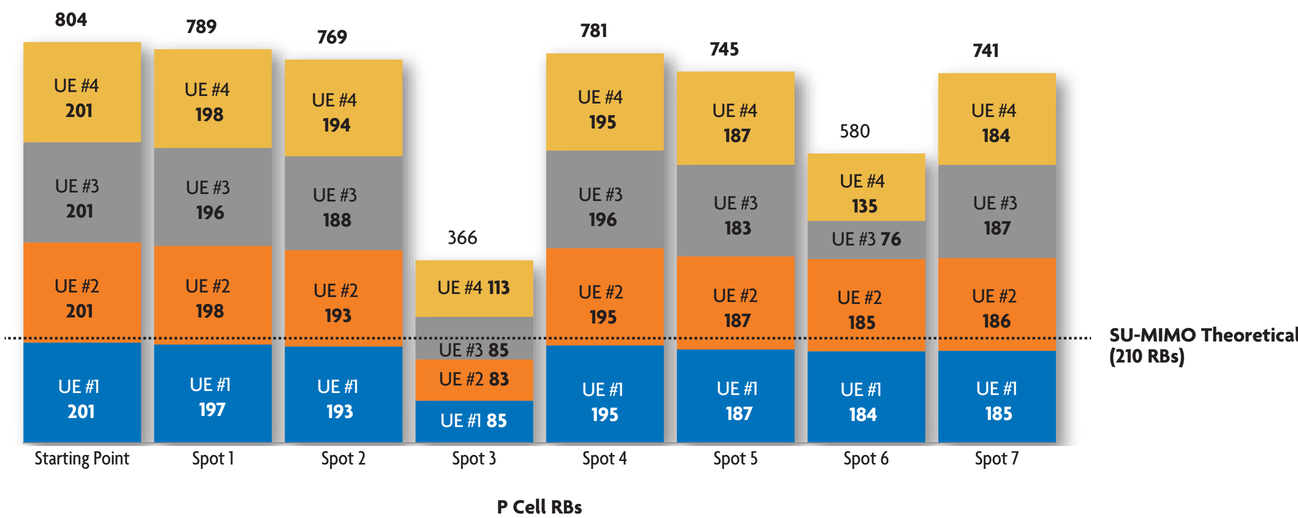
The next three figures show the average throughput (Figure 39) average RB allocations (Figure 40) and average MIMO layers (Figure 41) at the starting location for UE #4 as well as the seven stationary test points. At each location, the MU-MIMO results exceeded / greatly exceeded what would have been possible with SU-MIMO.

Figure 39. Test Case 12 Average Downlink Throughput with MU-MIMO



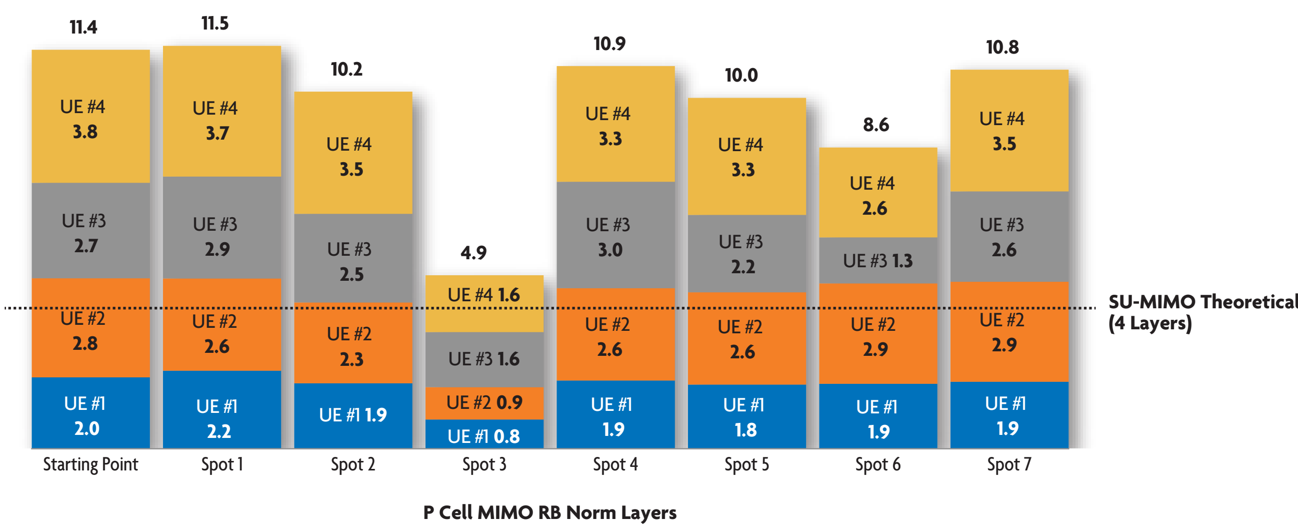
Source: Signals Research Group

Figure 40. Test Case 12 Average Resource Block Allocations with MU-MIMO



Source: Signals Research Group

Figure 41. Test Case 12 Average MIMO Layers with MU-MIMO



Source: Signals Research Group

For Test Case 7 (Figure 42), we're highlighting the performance of the secondary cell and how it performed with four smartphones receiving data, compared with the primary cell. Since the secondary cell did not support MU-MIMO, this comparison helps illustrate the benefits of MU-MIMO. The secondary cell in the network we tested had a channel bandwidth of 40 MHz, so its total capacity was inherently lower than what was possible with the primary cell. Nonetheless, it is evident in the test results that the secondary cell total throughput remained unchanged between the single phone data transfers and the multi-phone data transfers while with MU-MIMO there was an obvious increase in the total throughput for the primary cell.

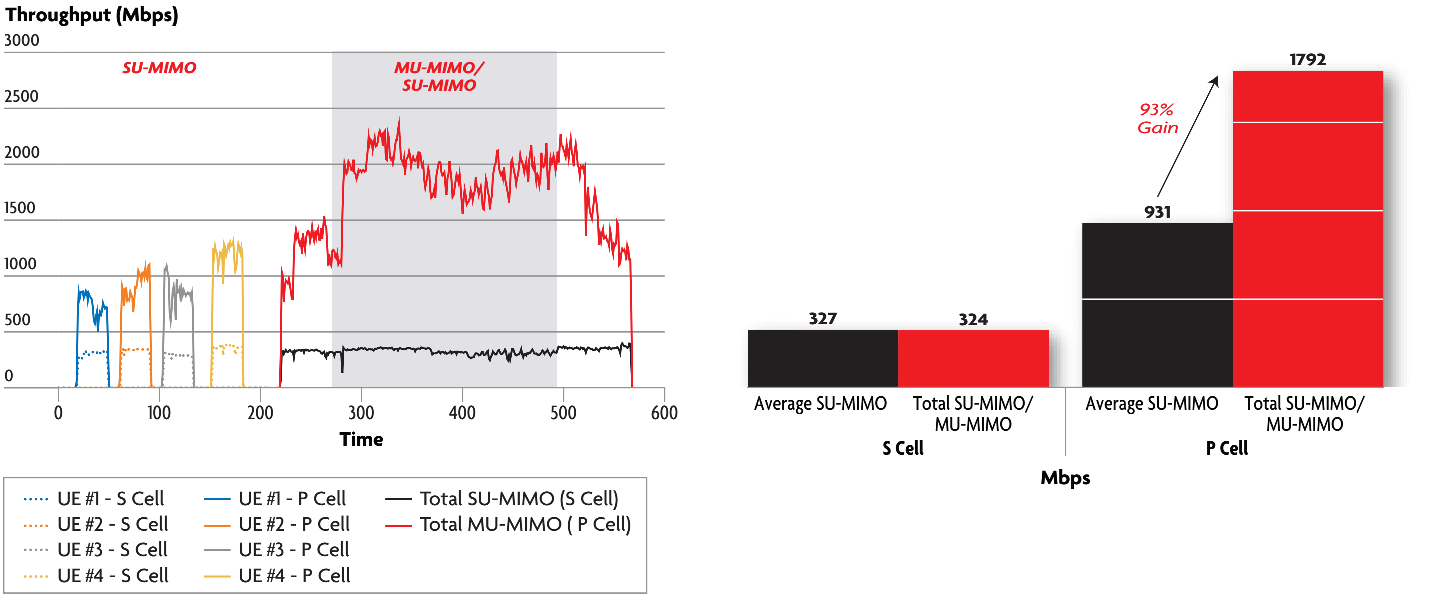
Figure 42. Test Case 7 Mobile Phone Locations and Key RF Metrics

	RSRP (dBm)	SINR (dB)	Cell Site Distance (m)	Angle of Arrival (°)
UE #1	-74.9	23.9	43	208
UE #2	-82.9	7.3	83	277
UE #3	-68.5	26.0	68	229
UE #4	-74.9	23.9	100	268

Source: Signals Research Group

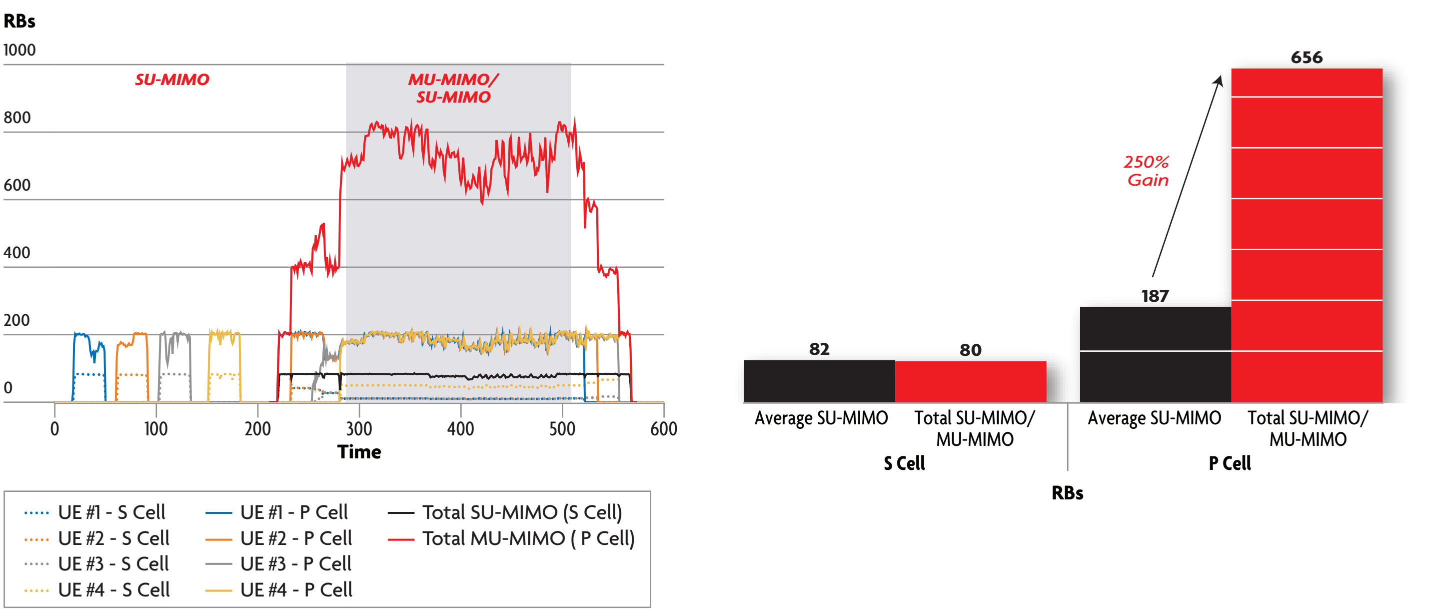
Figure 43 (throughput) and Figure 44 (resource blocks) show the primary cell and secondary cell performance with individual smartphones receiving data during the first 200 seconds of the test and how the primary cell and secondary cell performed with all four smartphones receiving data during the remainder of the test. With the primary cell, the average sector throughput increased by 93%, thanks to a 250% increase in RB usage, while in the secondary cell, the throughput and RB allocations remained largely equal during the two portions of the test.

Figure 43. Test Case 7 Downlink Throughput Comparison Between MU-MIMO and SU-MIMO



Source: Signals Research Group

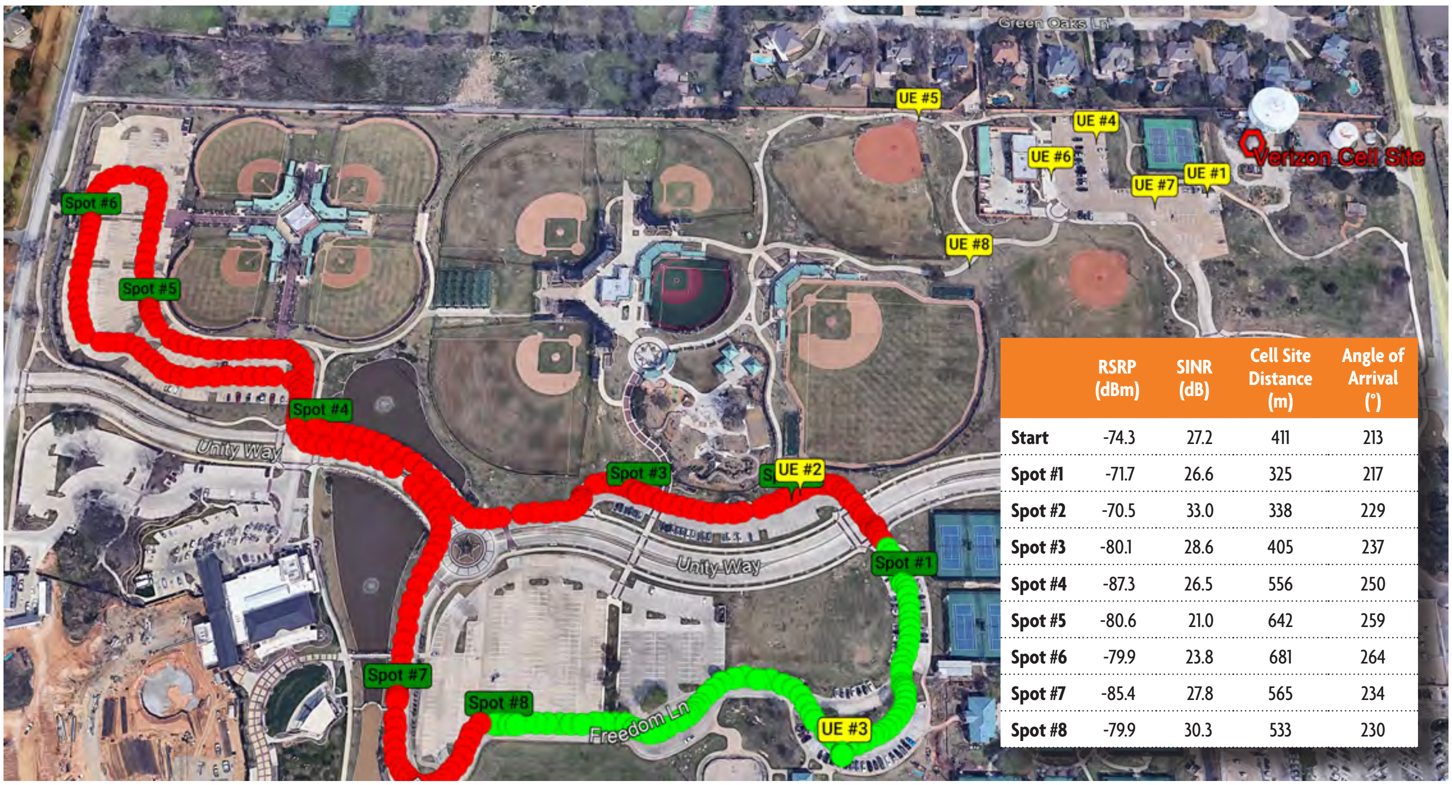
Figure 44. Test Case 7 Resource Block Allocations Comparison Between MU-MIMO and SU-MIMO



Source: Signals Research Group

The last two test cases in this appendix stem from two different drive tests involving stationary phones and one phone in a moving vehicle. Test Case 17 leveraged eight smartphones with the phone labeled UE #5 being the phone that was in the moving vehicle. Figure 45 shows the drive route used for this test as well as the locations where we conducted stationary tests. The drive route is highlighted by red or green circles. The green circles indicate areas where the UE #5 was able to pair reasonably well with the other smartphones in the test while the red circles indicate areas where the phone was less successful in pairing. Even in those instances when UE #5 wasn't pairing well with the other phones, the remaining phones were still able to pair with each other, resulting in much higher throughput than possible with SU-MIMO.

Figure 45. Test Case 17 Mobile Phone Locations and Key RF Metrics

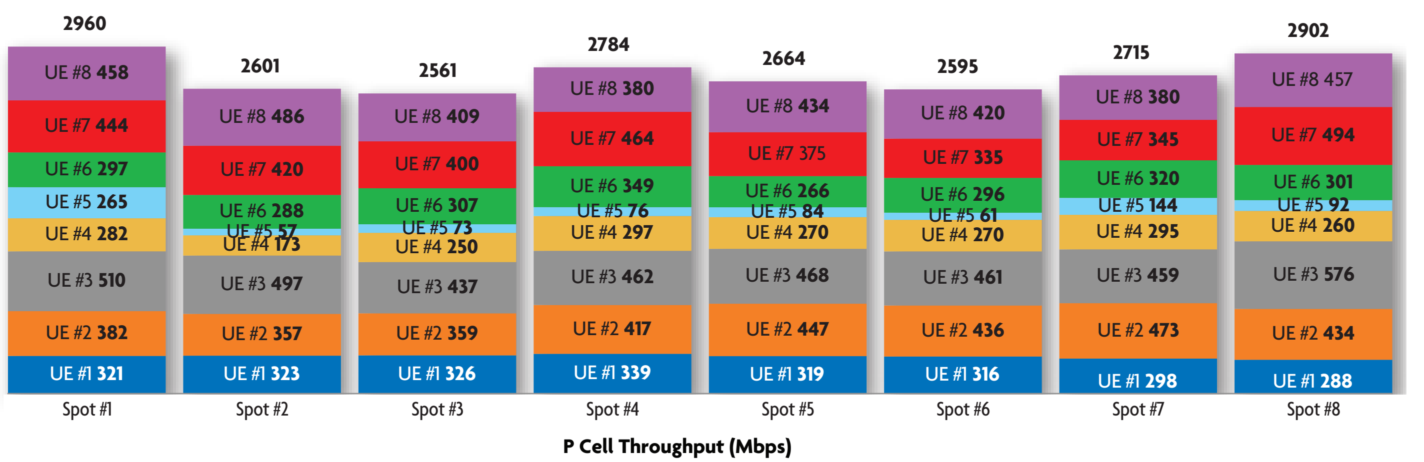


	RSRP (dBm)	SINR (dB)	Cell Site Distance (m)	Angle of Arrival (°)
Start	-74.3	27.2	411	213
Spot #1	-71.7	26.6	325	217
Spot #2	-70.5	33.0	338	229
Spot #3	-80.1	28.6	405	237
Spot #4	-87.3	26.5	556	250
Spot #5	-80.6	21.0	642	259
Spot #6	-79.9	23.8	681	264
Spot #7	-85.4	27.8	565	234
Spot #8	-79.9	30.3	533	230

Source: Signals Research Group

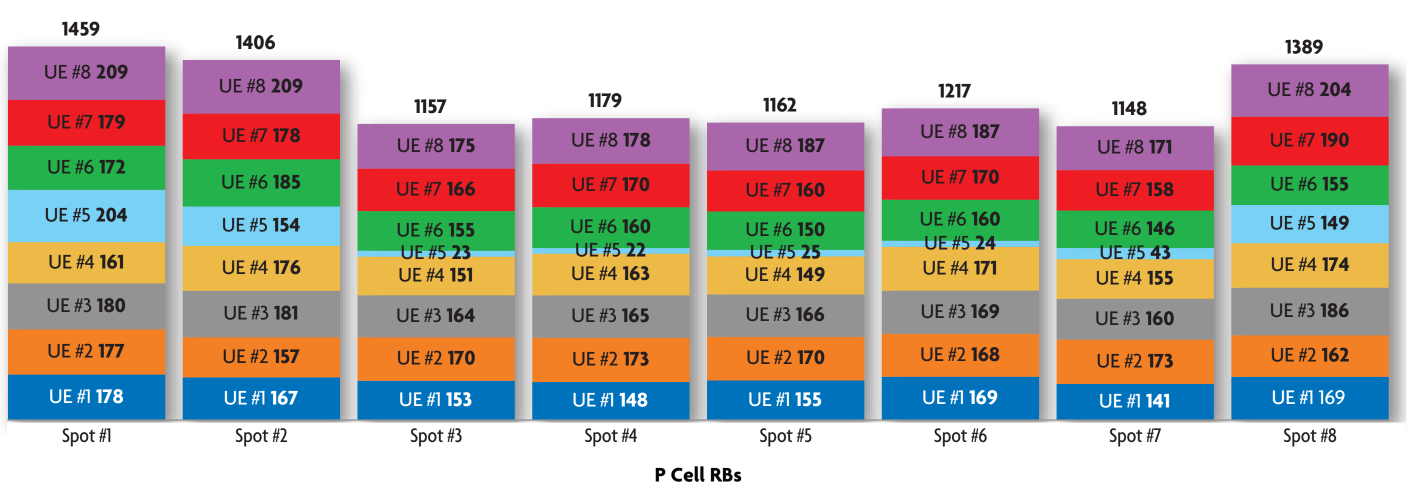
The next three figures show important performance metrics when UE #5 was at one of the 8 test locations. Figure 46 shows the average throughput, Figure 47 provides the average RB allocations and Figure 48 shows the average number of MIMO layers. At each location, the total throughput was at least 2x higher than what would have been achieved with SU-MIMO.

Figure 46. Test Case 17 Average Downlink Throughput with MU-MIMO



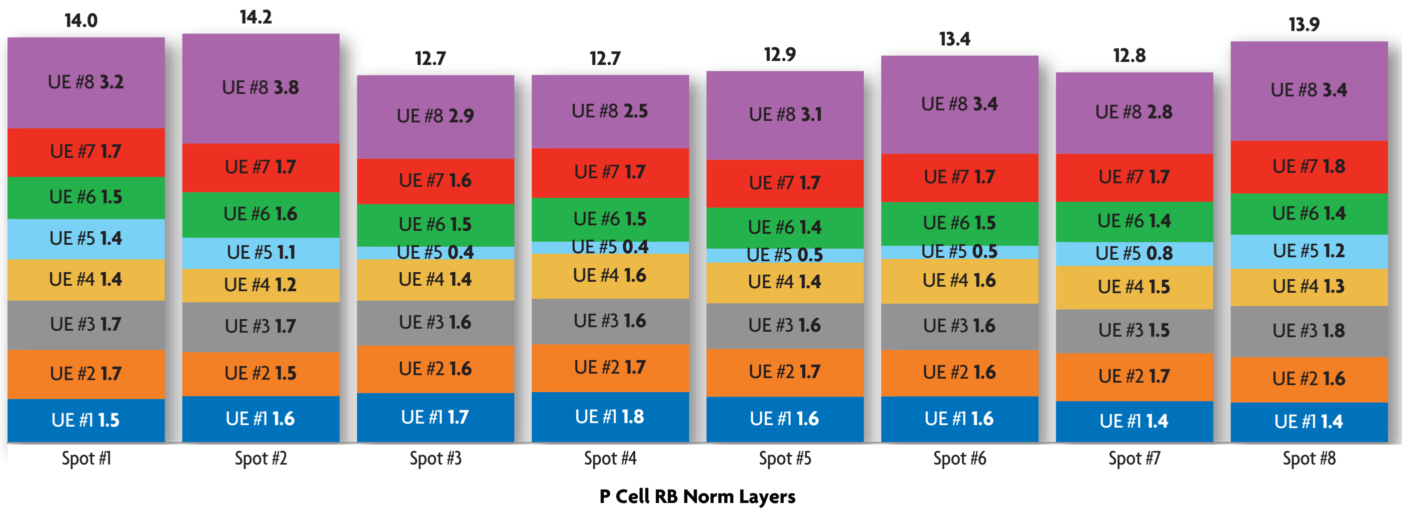
Source: Signals Research Group

Figure 47. Test Case 17 Average Resource Block Allocations with MU-MIMO



Source: Signals Research Group

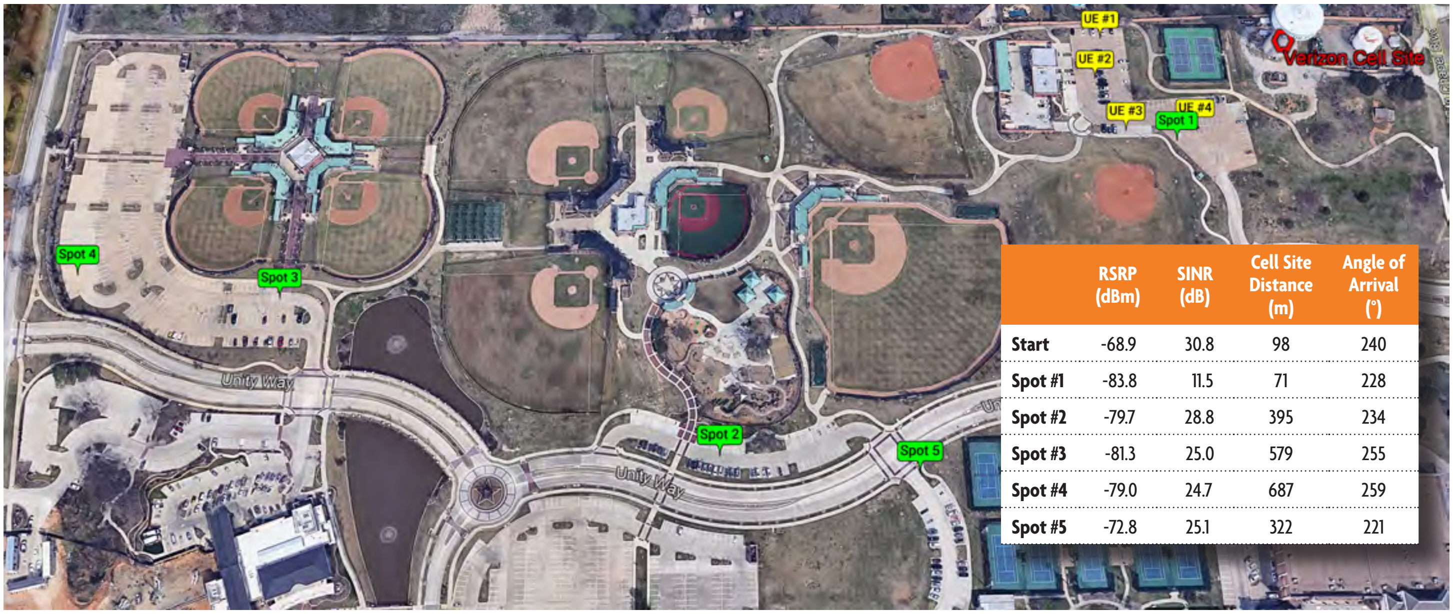
Figure 48. Test Case 17 Average MIMO Layers with MU-MIMO



Source: Signals Research Group

The last set of figures stems from an uplink drive test that included three additional stationary smartphones. We experienced some difficulties with the GPS logging on the smartphone in the moving vehicle, so we were not able to plot the entire drive route. We were, however, able to identify and plot the stationary locations, as shown in Figure 49.

Figure 49. Test Case 2 Mobile Phone Locations and Key RF Metrics

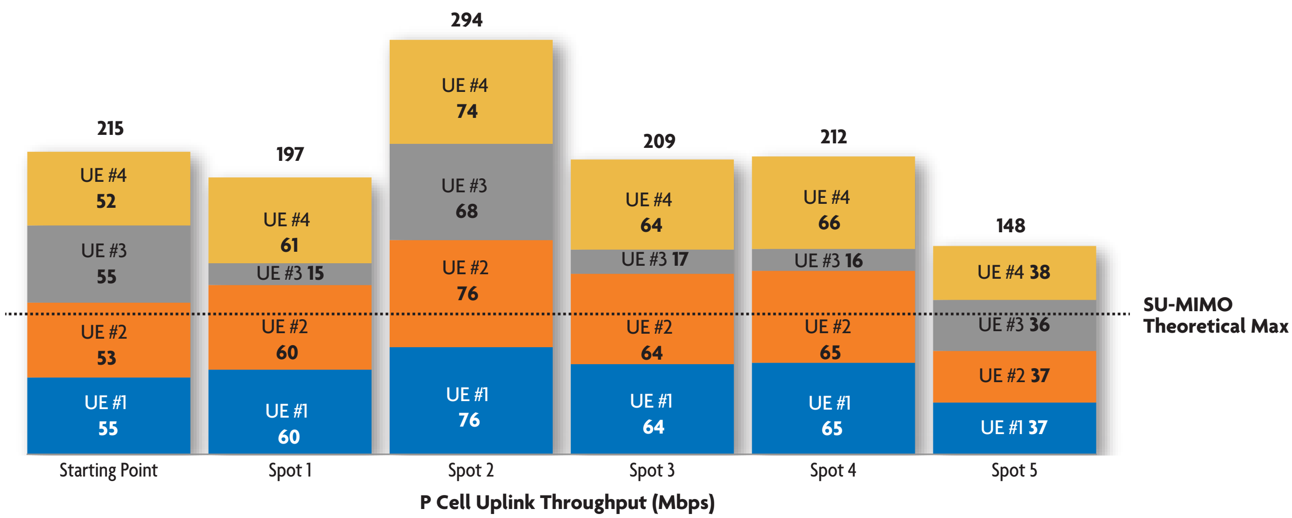


	RSRP (dBm)	SINR (dB)	Cell Site Distance (m)	Angle of Arrival (°)
Start	-68.9	30.8	98	240
Spot #1	-83.8	11.5	71	228
Spot #2	-79.7	28.8	395	234
Spot #3	-81.3	25.0	579	255
Spot #4	-79.0	24.7	687	259
Spot #5	-72.8	25.1	322	221

Source: Signals Research Group

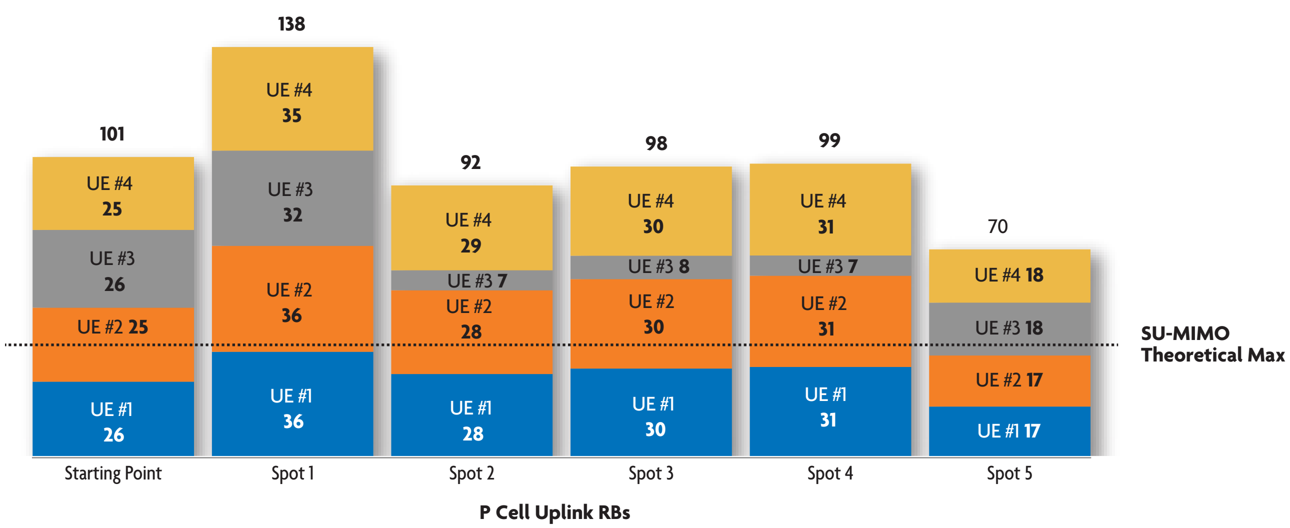
As shown in Figure 50 through Figure 52, uplink MU-MIMO delivered an average of nearly 150% higher throughput than possible with SU-MIMO, thanks to much more than 160% higher RB reuse and a corresponding increase in MIMO layers.

Figure 50. Test Case 2 Average Uplink Throughput with MU-MIMO



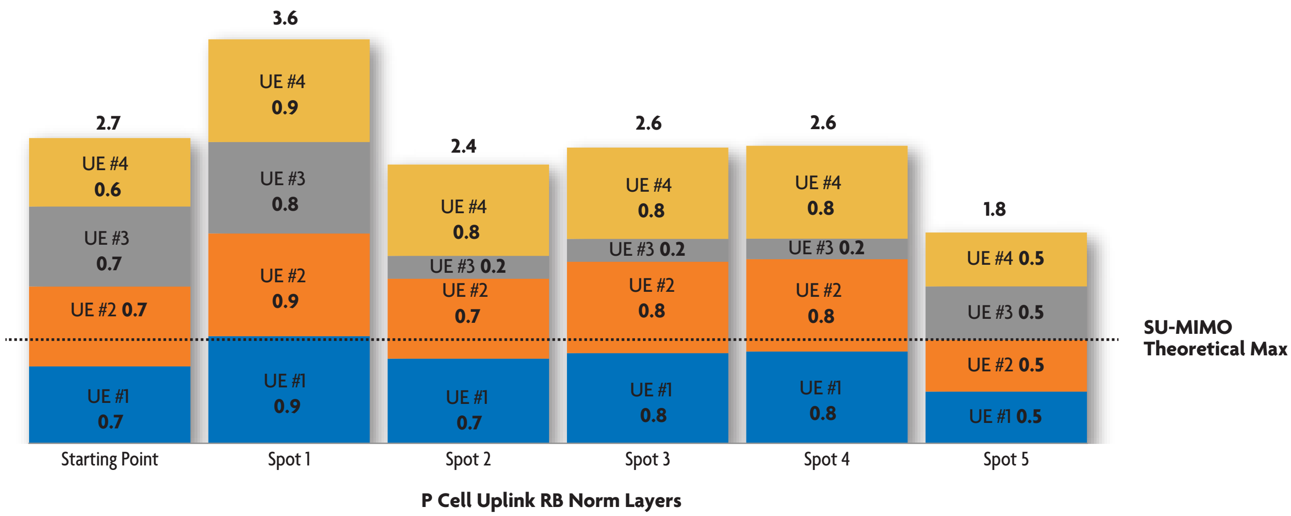
Source: Signals Research Group

Figure 51. Test Case 2 Average Resource Block Allocations with MU-MIMO



Source: Signals Research Group

Figure 52. Test Case 2 Average MIMO Layers with MU-MIMO



Source: Signals Research Group

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