PAVING THE WAY TO 5G SA WITH CARRIER AGGREGATION

A THIRD-PARTY BENCHMARK STUDY OF 5G FOUR COMPONENT CARRIER AGGREGATION

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Prepared by
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SIGNALS Research Group
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Study Conducted for Nokia

Signals Research Group conducted third-party testing of 5G four component carrier aggregation in a T-Mobile USA commercial 5G network where Nokia is the infrastructure supplier. We used a combination of commercial smartphones and a mobile test platform with soon-to-be-released modem functionality that supported the four 5G component carriers.

As the sole authors of this study, we stand fully behind the results and analysis that we provide in this paper. In addition to providing consulting services on wireless-related topics, including performance benchmark studies, Signals Research Group is the publisher of the *Signals Ahead* research newsletter (www.signalsresearch.com).

Signals Research Group (SRG) conducted a benchmark study of 5G four component carrier aggregation (4CC) in a T-Mobile USA commercial network located in Everett, Washington, where Nokia is the radio access and core network infrastructure supplier. In addition to testing in a network with live commercial traffic, we used a combination of commercial smartphones and a mobile test device with a soon-to-be-available 5G modem that supported 4CC functionality.

Key highlights include the following:

- **The gain in user throughput due to 4CC provides a more consistent user experience.** The expected gain in user throughput with 4CC largely depends on the mix of frequencies and channel bandwidths used by the operator. In our study the overall gains were relatively modest because we treated the operator's two Band n41 TDD carriers (100 MHz + 40 MHz) as the initial two carriers with the operator's two FDD carriers (15 MHz @Band n25 and 15 MHz @Band n71), as the two additional 5G carriers. Nonetheless, there was a double-digit percentage increase in total throughput, including a 20% increase in data speeds at the 10th percentile, or areas in the network where the radio conditions are the most challenging and where higher data speeds may be necessary.

- **FDD-TDD carrier aggregation delivers a meaningful increase in the mid-band 5G coverage.** With FDD-TDD carrier aggregation (CA), the smartphone uses a low-band FDD carrier as its primary cell (P cell), which results in the lower frequency being used for the uplink ACK/NACK messages for all secondary carriers (S Cell), including mid-band 5G channels. Since the uplink is almost always the limiting factor that defines network coverage, by moving the uplink to a low-band FDD carrier, the coverage area of the mid-band 5G carrier(s) is increased, leading to higher downlink data speeds while also introducing higher spectral efficiency in the P cell uplink control channel transmissions. It wasn't uncommon in our tests to document at least a 2x increase in user data speeds, if not substantially higher, due to FDD-TDD CA. And with 4CC, the smartphone can always use the low-band frequency(ies) as an S cell without a capacity penalty that could occur in a 2CC network with two mid-band 5G channels.

- **Carrier aggregation and a 5G Standalone (SA) architecture, can significantly increase battery life, depending on the use case.** With full buffer downlink data transfers using 2CC and 5G SA, we found the expected battery life was extended by 25% versus a single 5G carrier. Going from a Non-Standalone (NSA) 1CC architecture to 5G SA 2CC increased the expected battery life by nearly 90% with continuous full buffer data transmissions. With lower bit-rate data transmissions, it is more energy efficient to use a single carrier, assuming it doesn't degrade the user experience. Nokia's stepwise scheduling algorithm monitors the scheduling buffer and only activates carrier aggregation when it is necessary.

A special thanks to Accuver Americas (XCAL5) and Spirent Communications (Umetrix Data) for the use of their respective drive test tools and test platforms. They have been invaluable partners for SRG for more than a decade.

The Gain in User Throughput Due to 4CC Provides a More Consistent User Experience

With 5G carrier aggregation (CA), multiple individual 5G carriers can be combined in a logical manner to significantly increase user throughput over what is possible with a single 5G carrier. LTE went down the CA path and now 5G is following suit. Most operators have at least one mid-band 5G channel and some fortunate operators have two or more mid-band 5G channels. These mid-band channels are critical as a 5G marketing differentiator since with wider channels come higher data speeds. 5G currently supports up to 100 MHz channel bandwidths while LTE is limited to 20 MHz.

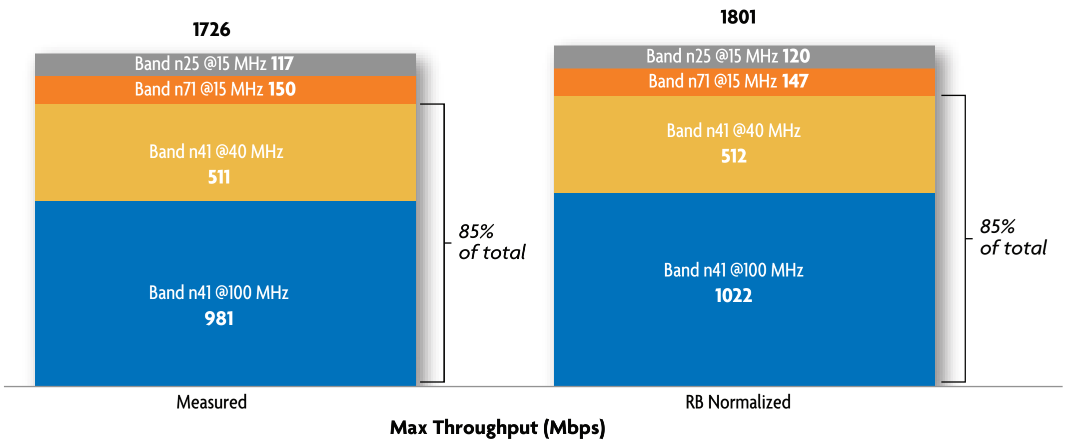
The challenge comes when operators use narrower channel bandwidths for 5G since the achievable data speeds with this spectrum do not deliver the data speeds frequently associated with 5G. Combining these narrow bandwidth channels with wider bandwidth channels via 5G CA allows an operator to gain more 5G capacity, fully leverage all spectrum assets for 5G, and even achieve higher data speeds than possible with just the mid-band spectrum. As shown in the next section, these narrow channels, which typically reside in lower frequencies, offer an even more compelling reason to deploy higher orders of 5G CA.

T-Mobile USA is one of the fortunate operators to have ample mid-band spectrum for 5G. The operator has already deployed a 100 MHz channel and a companion 40 MHz channel with 5G CA logically combining those two channels to deliver even higher data rates than possible with a single 100 MHz channel. With Nokia's support of 4CC in the operator's network, T-Mobile USA is capable of delivering even higher data speeds to its customers.

Figure 1 shows the maximum physical layer throughput we observed when testing with a mobile test device at a location with good (not great) radio conditions. The figure shows both the measured throughput and the Resource Block (RB) normalized throughput in which we grossed up the measured throughput to account for network resources (RBs) that the network scheduler didn't allocate to our mobile test device. In effect, RB normalized throughput shows the potential throughput for the given radio conditions in an empty network without other commercial traffic. The Band n25 and Band n71 throughput at the one-second time interval shown in the figure were much different despite the identical channel bandwidth, suggesting even higher throughput was possible – perhaps achievable with a commercial smartphone that has a well-optimized RF frontend. The measurement values in each stacked bar occurred at slightly different times during the test, hence it isn't possible to directly compare throughput and RB normalized throughput between the two sets of results.

The mix of an operator's low-band and mid-band 5G spectrum assets determines the maximum gain possible by deploying 5G 4CC.

Figure 1. 4CC Maximum Throughput



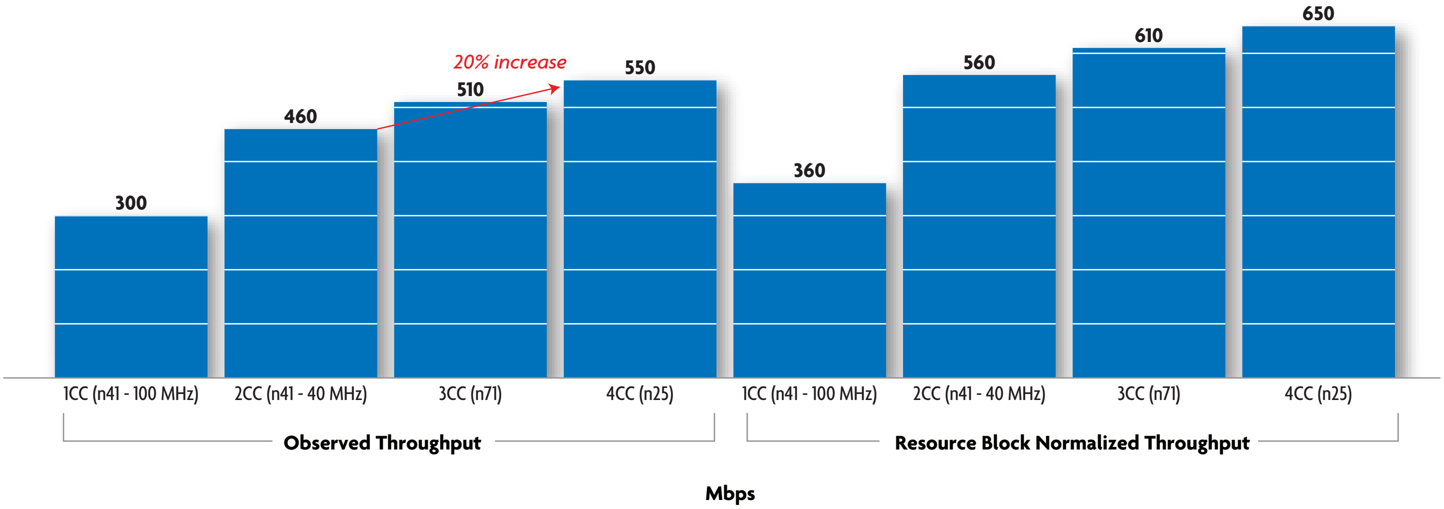
Source: Signals Research Group

With 140 MHz of mid-band 5G spectrum (Band n41) and only 30 MHz of total low-band FDD spectrum for 5G, it isn't surprising that Band n41 carried the majority of the total throughput. Mobile operators with less mid-band 5G spectrum (e.g., a single 50 MHz or 100 MHz channel) and more low-band FDD spectrum (e.g., 3x20 MHz) will achieve a much higher increase in total throughput when deploying 4CC.

Higher maximum data speeds are nice, and perhaps useful for marketing purposes, but the real benefit of 5G 4CC is that it can deliver a more consistent user experience, especially with more challenging radio conditions. Figure 2 shows the results from a different test from the results shown in the previous figure. In this case we conducted a drive test with the mobile test device in a cluster of cell sites with 4CC functionality and 10 Gbps backhaul. Specifically, the figure shows the individual contributions from each component carrier at the 10th percentile, likely edge of cell or other locations with sub-optimal RF conditions. In our tests, the move from 2CC to 4CC increased the physical layer throughput by 20% at the 10th percentile. And as discussed in the next section, when 4CC is combined with FDD-TDD CA, the increase in throughput can be far more substantial. Operators with a less attractive mix of mid-band/wide bandwidth and low-band/narrow bandwidth spectrum assets would almost certainly achieve a much higher gain in throughput than what we documented in our tests.

5G 4CC can deliver a more consistent user experience, especially with more challenging radio conditions.

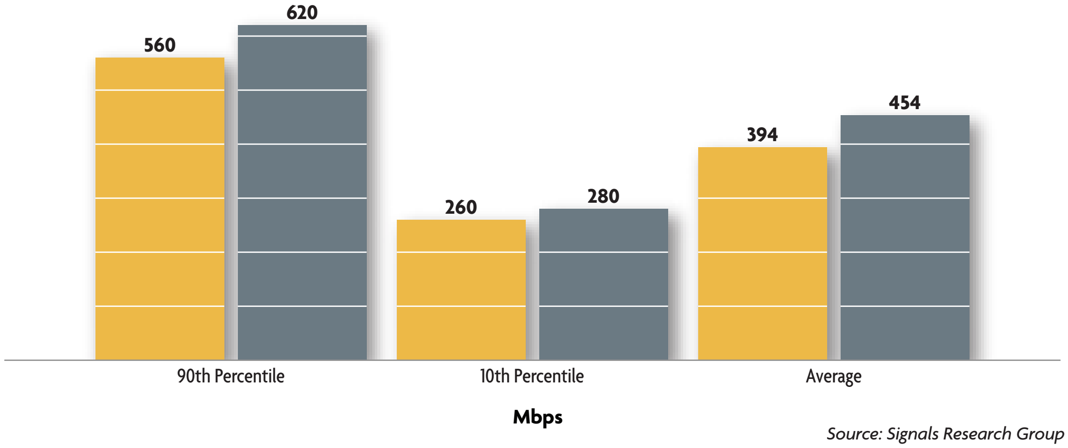
Figure 2. 4CC Smartphone Throughput – 10th Percentile



Source: Signals Research Group

In yet another test, we drove in the commercial cluster with two devices – the mobile test device with 4CC capability and a Galaxy S22, which at the time we did our tests was limited to 2CC. The Galaxy S22 smartphone now supports 3CC functionality following a recently-released software upgrade. Figure 3 shows comparative throughput results at the 10th percentile, 50th percentile, and 90th percentile.

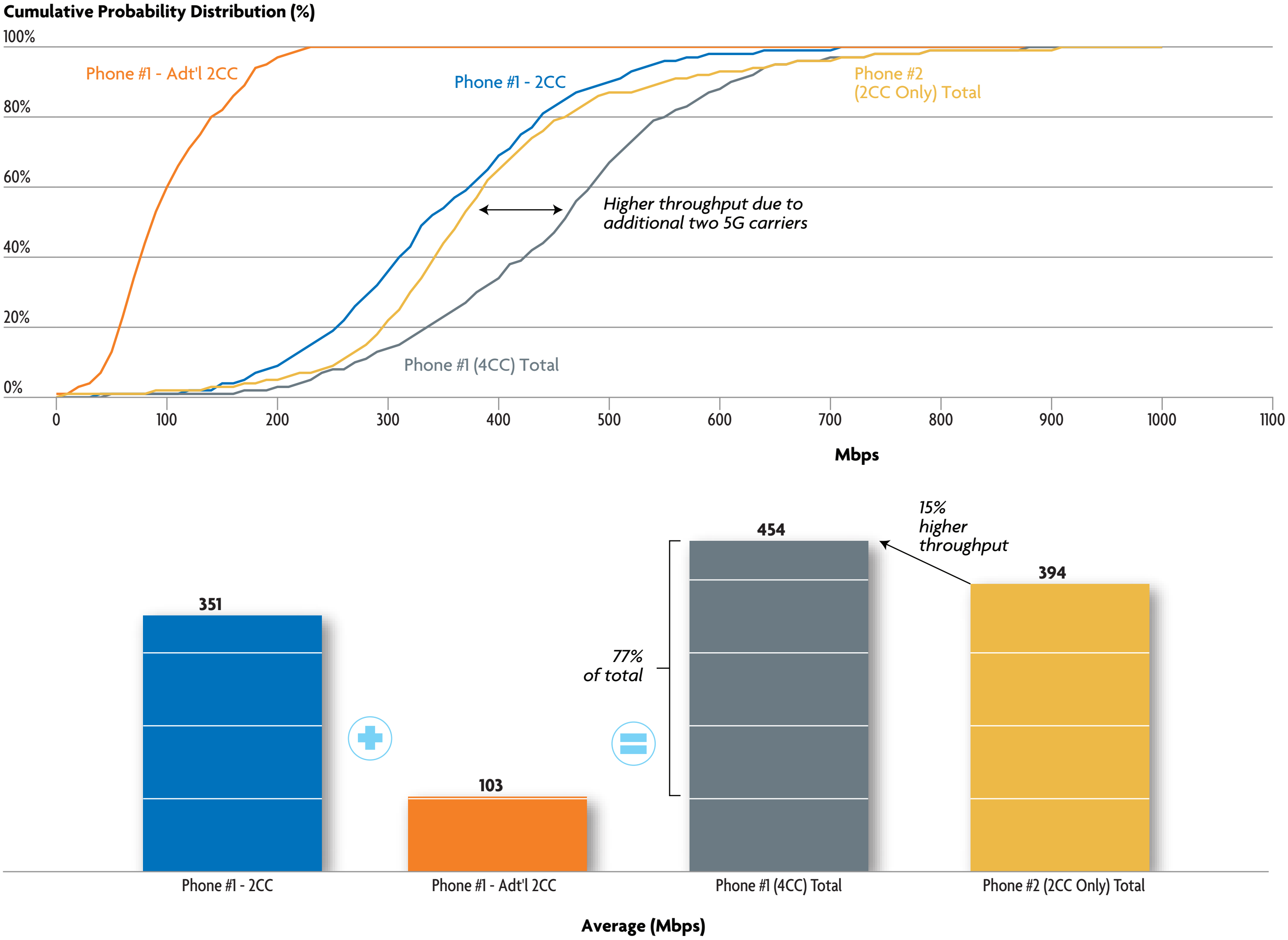
Figure 3. 4CC Smartphone Versus 2CC Smartphone



Source: Signals Research Group

Figure 4 provides the same information with a bit more detail. The top figure shows the cumulative distribution of throughput for the two devices. For the mobile test device, we combined the throughput from each individual carrier such that the contributions from the two Band n41 channels is shown in "Phone #1 – 2CC" and the contributions from the two FDD bands is shown in "Phone #1 – Add'l 2CC." "Phone #1 (4CC) Total" illustrates the total throughput for the 4CC-capable mobile test device. In this test, the two Band n41 carriers accounted for 77% of the mobile test device's total throughput, ultimately resulting in the 4CC-capable mobile test device achieving 15% higher throughput than the Galaxy S22 smartphone.

Figure 4. 4CC Smartphone Versus 2CC Smartphone Throughput Distribution



Source: Signals Research Group

FDD-TDD Carrier Aggregation Delivers a Meaningful Increase in the Mid-band 5G Coverage

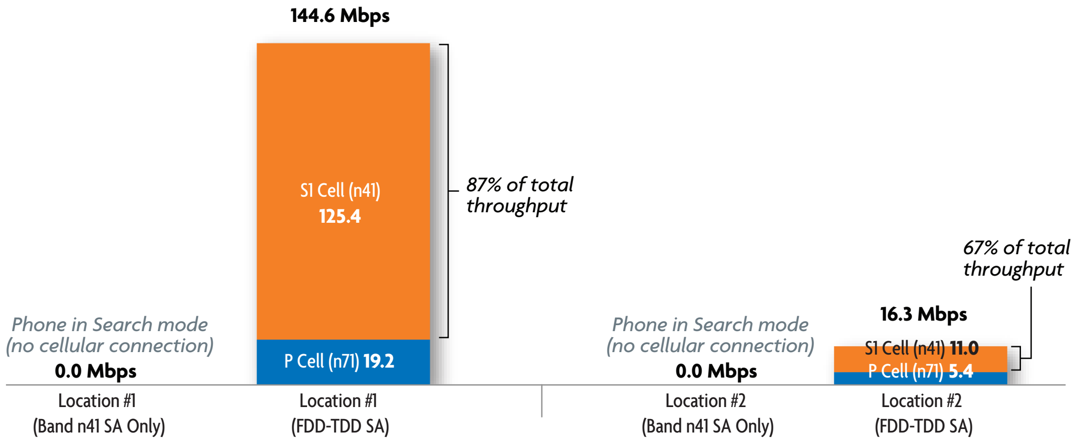
FDD-TDD CA, in combination with 5G 4CC functionality, provides gains in both coverage and capacity. The philosophical debate on FDD versus TDD positioned FDD as a duplex scheme that offered better coverage than TDD with the tradeoff being lower downlink capacity than TDD. Conversely, TDD was argued to have much better capacity than FDD with the disadvantage being reduced coverage. Both arguments have their validity, but with FDD-TDD CA it doesn't matter because the network simultaneously supports both duplex schemes – TDD in the mid-band spectrum and FDD in the low-band spectrum.

5G 4CC takes the concept of FDD-TDD CA to the next level since with four active 5G carriers serving the smartphone, the phone can continue using a low-band FDD carrier while also using two or even three mid-band 5G channels. With a network and smartphones limited to 2CC, our experience was that one of two situations occurred:

- With good RF conditions, the smartphone only used two mid-band 5G channels so there wasn't a seamless transition to FDD-TDD when warranted, plus the smartphone was missing out on the additional capacity offered by the FDD channel (now two channels with 4CC).
- With poorer RF conditions, the smartphone had to drop one of the two mid-band 5G channels so that it could use the FDD channel to maintain 5G coverage.

Figure 5 shows two locations where FDD-TDD CA provided an obvious benefit. Ironically, we captured these results in proximity to SRG Headquarters, albeit still on T-Mobile's commercial network and with Nokia infrastructure. At both locations (Location #1 and Location #2) the smartphone remained in search mode with no network signal when the smartphone was locked to Band n41 SA mode. There was LTE coverage but for purposes of this test, we wanted to evaluate network performance in the absence of an LTE anchor band. With FDD (Band n71) enabled on the phone along with Band n41, the Galaxy S22 smartphone used Band n71 as its P Cell and it was able to use the 100 MHz Band n41 channel as its S1 Cell.

Figure 5. FDD-TDD Carrier Aggregation and Downlink Data Speeds



Source: Signals Research Group

At Location #1, the use of FDD-TDD CA increased the end user throughput from a somewhat satisfactory 19.2 Mbps to an impressive 144.6 Mbps – an increase of 6.6x. Band n41 accounted for 87% of the total throughput. At Location #2, the impact of Band n41 wasn't as meaningful on an absolute basis, but its inclusion took an otherwise poor data speed to a data speed that would be more than adequate for many applications. It is worth reiterating that at both locations, if there wasn't FDD-TDD CA then there wouldn't be any mid-band 5G coverage.

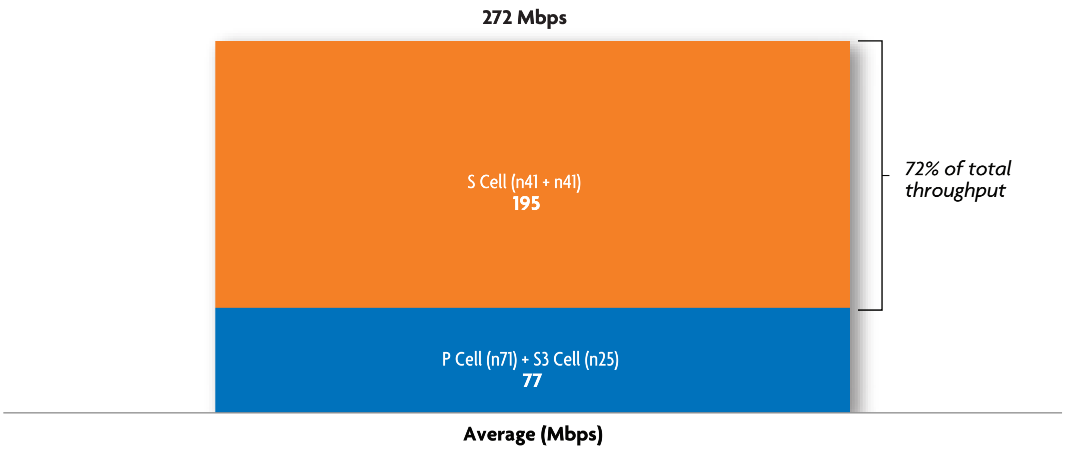
FDD-TDD CA increased the end user throughput from a somewhat satisfactory 19.2 Mbps to an impressive 144.6 Mbps – an increase of 6.6x.

Returning back to test results from Washington, we collected additional data during walk tests which demonstrate the benefits of FDD-TDD CA. Quite frankly, we've done a lot of testing on T-Mobile's 5G network over the last couple of years and it is challenging to find outdoor areas in urban environments where FDD-TDD CA is necessary for mid-band coverage extension. Most operators don't have this luxury, plus the in-building penetration loss at the higher frequencies is an important consideration that impacts all operators. For these reasons, and since there were very few publicly accessible buildings in the area where we did these tests, we moved to lower levels of a parking garage until we reached a point where the mobile test device could no longer use Band n41 as the P Cell, at which point the mobile test device used FDD-TDD CA.

Figure 6 shows the average throughput for the two FDD carriers and the average throughput for the two TDD carriers when the mobile test device used FDD-TDD CA. In the absence of any carrier aggregation, the mobile test device throughput would have been only 35 Mbps, or the n71 portion of the total FDD contribution. With the two FDD bands providing 2CC CA functionality, the average throughput was 77 Mbps. Finally, with FDD-TDD and 4CC CA, the average throughput increased to a much more impressive 272 Mbps, with the two Band n41 carriers accounting for 72% of the total throughput.

With 4CC CA and FDD-TDD CA, the average throughput increased to 272 Mbps, with the two Band n41 carriers accounting for 72% of the total throughput.

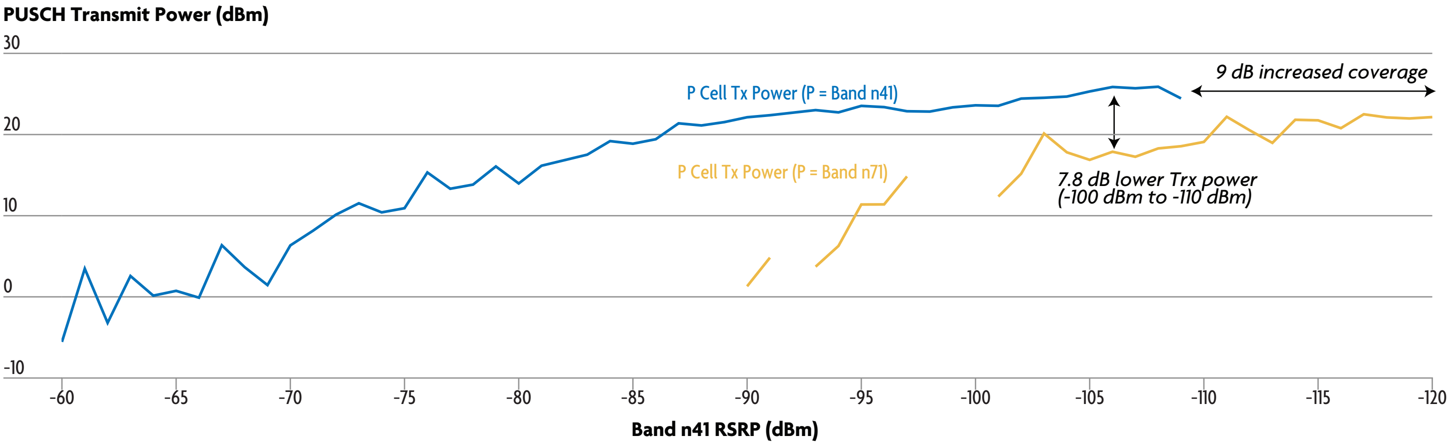
Figure 6. FDD-TDD Carrier Aggregation and Downlink Data Speeds, II



Source: Signals Research Group

Figure 7 shows two curves from the same walk test and provides some additional insight into how the results in the earlier figure were achieved. One curve plots the uplink transmit power on the P Cell when the mobile test device was using Band n41 as its P Cell. The other curve plots the uplink transmit power on the P Cell when the mobile test device was using Band n71 as its P Cell. The latter situation occurred when the Band n41 signal strength wasn't adequate to maintain an uplink connection on the P Cell, but the mobile test device still used Band n41 as an S Cell. One critical aspect of the figure is that in both cases the uplink transmit power was plotted as a function of its corresponding Band n41 signal strength, or RSRP. In the case of FDD-TDD CA, the Band n41 channels were secondary cells while with TDD-TDD CA, the P Cell was the 100 MHz Band n41 channel.

Figure 7. FDD-TDD Coverage Extension



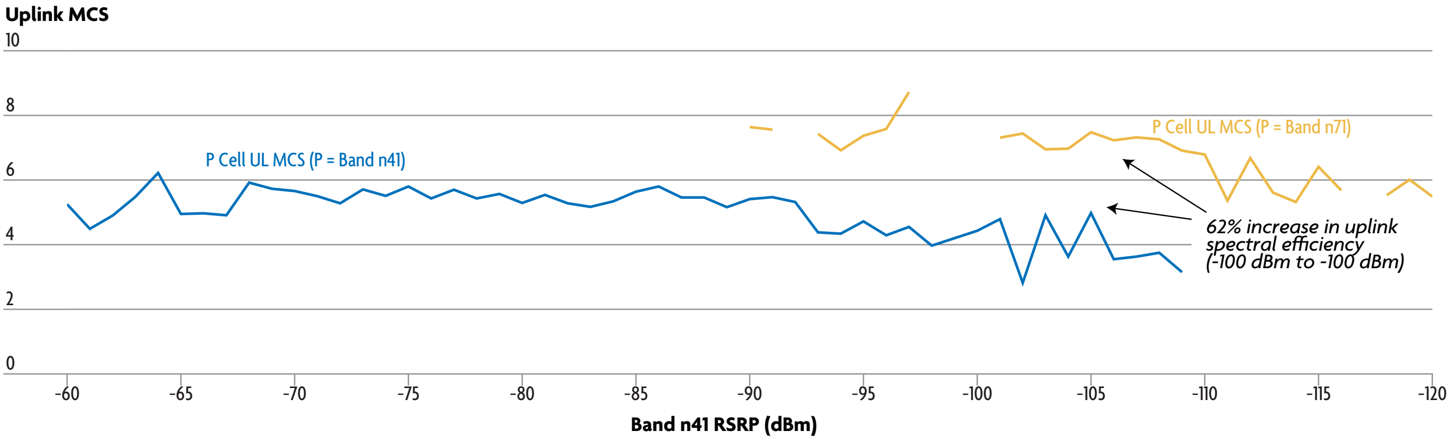
9 dB increased coverage

7.8 dB lower Trx power (-100 dBm to -110 dBm)

Source: Signals Research Group

Finally, as shown in Figure 8 when a low-band FDD carrier is used as the P Cell with FDD-TDD CA, there can be a meaningful increase in the uplink spectral efficiency associated with the uplink ACK/NACK messages. The figure shows the uplink MCS values as a function of the Band n41 RSRP. When the Band n41 RF conditions were poor and the P Cell was Band n71, the spectral efficiency with lower signal strength was more than 60% higher than it was when Band n41 was serving as the P Cell.

Figure 8. FDD-TDD Uplink Spectral Efficiency Gain



62% increase in uplink spectral efficiency (-100 dBm to -100 dBm)

Source: Signals Research Group

In its FDD-TDD CA implementation, Nokia supports seamless handovers between TDD-FDD CA and FDD-TDD CA by leveraging previous measurement reports for the S Cell so that a measurement gap isn't required when moving the S Cell to the P Cell. This feature reduces the interruption in the ongoing data activities that would otherwise occur with the gap needed for a measurement report.

Carrier Aggregation and a 5G Standalone (SA) Architecture, Can Significantly Increase Battery Life, Depending on the Use Case

When operators first launched LTE CA, we evaluated the impact of CA on battery life. Our analysis determined that LTE CA was more energy efficient, meaning that less energy was required to download data content with LTE CA than with a single LTE carrier. Put another way, although LTE CA had a higher current drain than downloading data with a single LTE carrier, the faster download time more than offset the higher current drain, resulting in an overall energy savings. As expected, the energy efficiency argument extends to 5G CA.

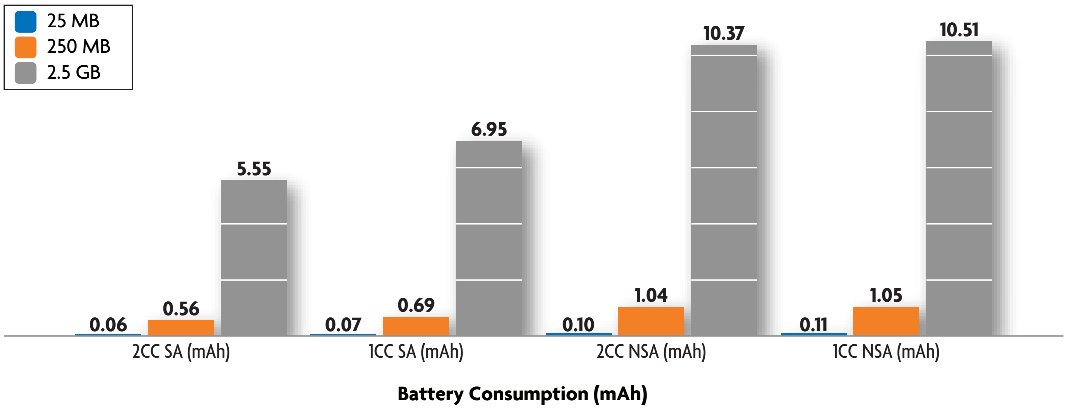
For this study we measured the current consumption on a Galaxy S22 smartphone during a 100 second full buffer HTTP data transfer. By comparing the measured data speed (application layer) with the battery current generated during the data transfer we could calculate the energy efficiency (Mbps/mA). For our analysis, we netted out the impact of the backlight display by measuring the current drain with the smartphone in airplane mode and with the backlight display illuminated. With the support of the operator, we were also able to do the tests with Band n41 CA disabled in the network, so the smartphone only used a single 100 MHz carrier for the 1CC tests. Ultimately, we did these tests with the smartphone in four different configurations: 1CC and 2CC (100 MHz + 40 MHz in Band n41) and in NSA and SA modes of operation.

Using the measured data speeds at the application layer, along with the associated current drain, we calculated how much battery energy was required to download a file/data content with three different file sizes. Figure 9 shows the results of this study. Obviously, more energy was required to download a 2.5 GB file than a 25 MB file, regardless of the phone + network configuration. The more interesting analysis stems from comparing results across configurations.

5G 2CC SA was the most energy efficient combination we tested while 5G 1CC NSA was the least energy efficient. In fact, as shown in Figure 10, 5G 2CC SA was 89% more energy efficient than 5G 1CC NSA. Compared with 5G 1CC SA, moving to 2CC SA resulted in a 25% increase in energy efficiency. We did these tests with a commercial smartphone, which was limited to 2CC, since we did not believe the mobile test device was optimized for energy consumption. It is our expectation that future tests with a commercial smartphone supporting 4CC will achieve directionally similar results – an increase in energy efficiency with an increase in the number of component carriers.

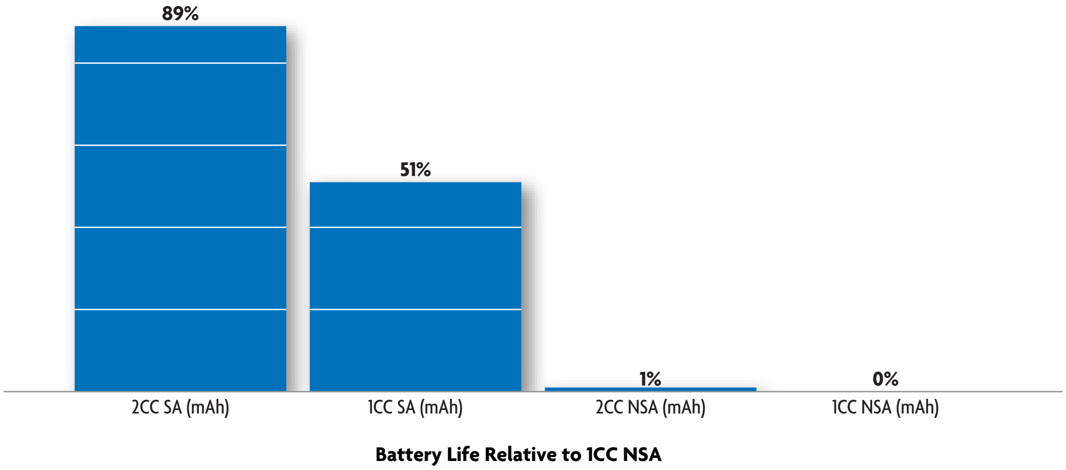
5G 2CC SA was 25% more energy efficient than 5G 1CC SA.

Figure 9. Carrier Aggregation and 5G Standalone Energy Requirements



Source: Signals Research Group

Figure 10. Carrier Aggregation and 5G Standalone Current Efficiency Gains Relative to 1CC NSA



Source: Signals Research Group

The energy efficiencies of carrier aggregation apply to instances involving full buffer data transfers, meaning any scenario when the smartphone is trying to download content as fast as possible (email synchs, file/social media downloads, etc.). Therefore, one shouldn't expect these types of gains with normal usage which involves a mix of user behavior, for example, screen time without any mobile data transactions. In fact, since carrier aggregation does have higher energy requirements, which can be more than offset by faster downloads, it is also the case that carrier aggregation can have a negative impact on energy efficiency if the network assigns carrier aggregation when it isn't needed.

In our tests, we purposefully set the download transfer rate to four thresholds: 120 kbps, 5 Mbps, 25 Mbps, full-buffer, and repeated these tests. With the exception of the full-buffer tests, we observed the network only assigned the smartphone the single 100 MHz Band n41 channel since that channel was more than capable of handling the data transfer without any degradation in the user experience. Nokia's CA implementation uses step wise buffer-based activation (and deactivation) of carrier aggregation to only add (remove) 5G carriers when they are needed, based on a combination of network load and application requirements.

Final Thoughts

5G carrier aggregation is a logical step in the evolution of 5G and it is a critical component in the transition to an all 5G network. Many operators around the world have deployed at least a single 5G carrier, some operators have deployed 5G 2CC, and even a few operators are in the process of rolling out 5G 3CC and 5G 4CC functionality. Leading smartphone and chipset suppliers support, or will soon support, multi-carrier functionality and from a network perspective Nokia is already supporting 5G 4CC CA in an operator's commercial 5G network.

Although 5G 4CC is in its early stages, our test results document many of its inherent benefits. Increasing the number of component carriers boosts user data speeds, and while consumers may not realize the increased speeds when high data rates already exist, they will notice the benefits when sub-optimal radio conditions are present. Examples include edge-of-cell and in-building use cases. Furthermore, operators will eventually need to deploy 5G in narrower radio channels which can't deliver the data speeds possible with the wider channels that exist in the mid-band frequencies, not to mention meet the implicit expectations of 5G performance. 5G CA using three or more component carriers is the only means to extend 5G to these bands while continuing to leverage the capacity and speeds possible with the wider mid-band channels. Additionally, the lower FDD radio channels offer an inherent coverage benefit, which can even help extend the range of the 5G mid-band channels through the use of FDD-TDD CA.

Our test results document many of the inherent benefits of 5G 4CC.

It may not be on the immediate horizon for all operators, but eventually all operators will evolve their 5G networks to 5G SA to reap the many benefits of an all 5G network. 5G carrier aggregation, be it 3CC or 4CC today, increasing to even more 5G component carriers in the future, will inevitably play an important role in paving the way to a 5G Standalone network.

Appendix

Background

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

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

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

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

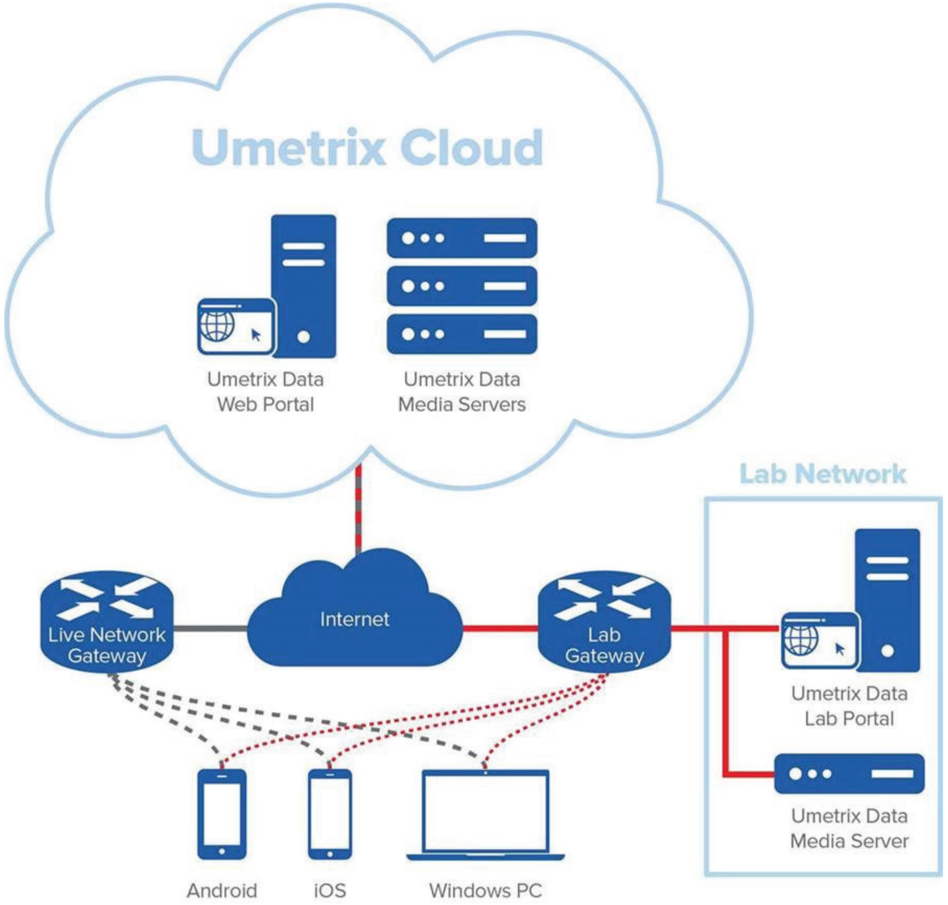
Test Methodology

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 to export the data for additional post processing and analysis. Spirent Communications provided its Umetrix Data platform which we used to generate the high bandwidth data transfers. Neither company had any direct prior knowledge of this study and SRG takes full responsibility for the data collection and analysis which were facilitated by their tools and platforms.

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

We used Umetrix Data for the data transfers from the network to the mobile devices. For most tests we used a full buffer HTTP data transfer from the Umetrix Data server located in southern California. The data transfers for the drive and walk tested lasted four minutes and repeated continuously for the duration of the tests. For the current measurement tests, we used a 100 second duration test profile, which we repeated twice. We also used Umetrix Data to capture the application layer throughput for these tests. It isn't possible to capture chipset diagnostic messages without connecting the phone via USB to a notebook computer, and since this action introduces a trickle charge to the phone, it negates the accuracy of the current drain measurement reports. We explain our current measurement tests in the next section where we provide some additional results, which we didn't include in the main body of this paper. Figure 11 illustrates the Umetrix Data network architecture.

Figure 11. Umetrix Data



Source: Spirent Communications

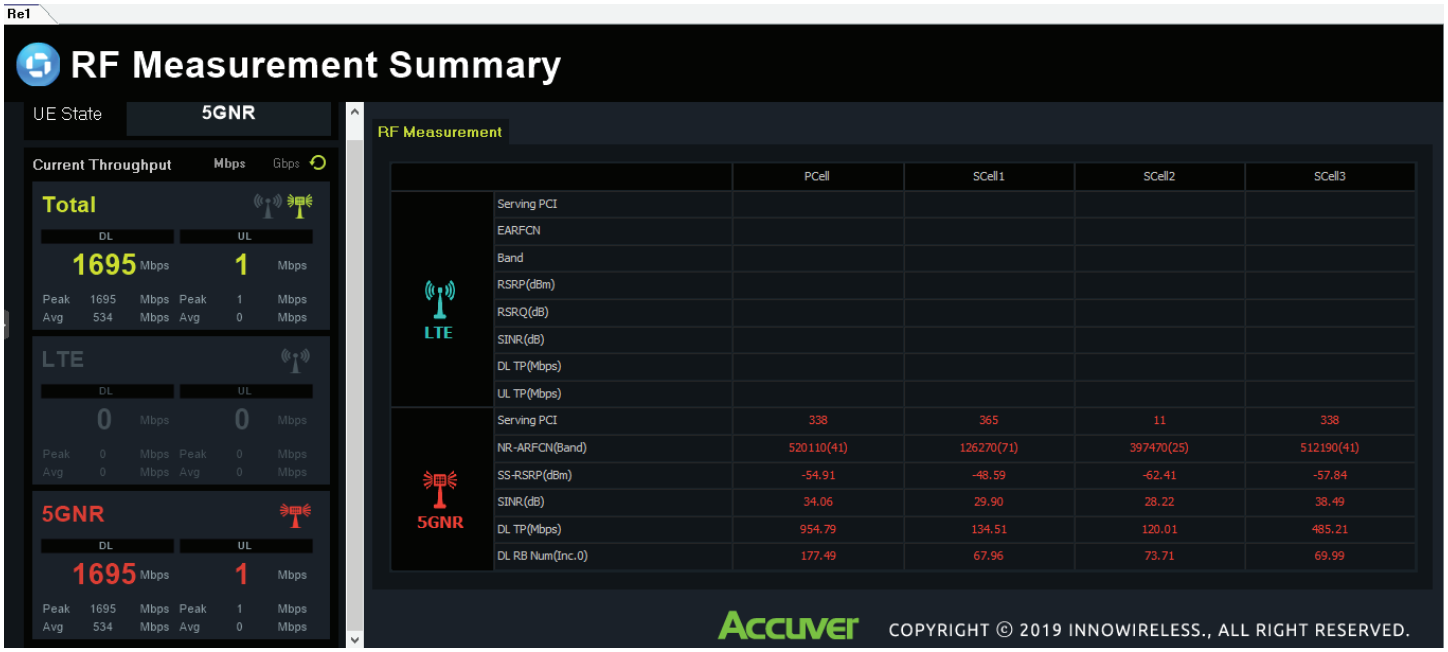
We used XCAL5 to collect chipset diagnostic messages from the mobile test device and smartphones. XCAL5 supports 5G chipsets from the three largest chipset suppliers, making it ideal to test with an assortment of smartphones and chipsets.

XCAL5 captures everything reported by the 5G chipset on a per TTI/slot-basis but for purposes of this study we relied primarily on physical layer parameters that provided information on the radio conditions, the achieved throughput, and the network resources (RBs) required to achieve the throughput. XCAL5 captured this information for each 5G and LTE component carrier, including other obvious metrics, like geo coordinates, frequency band and serving cell information (PCI).

We analyzed the data in one second time increments with each data point representing an average over that time frame. This approach is much less cumbersome than analyzing data on a per TTI/slot-basis while delivering nearly identical results.

Figure 12 shows a screen shot of the XCAL5 GUI which displays a few of the many metrics we could observe on a real-time basis.

Figure 12. XCAL5



UE State: 5GNR

	DL			UL	
Total	1695	Mbps		1	Mbps
Peak	1695	Mbps	Peak	1	Mbps
Avg	534	Mbps	Avg	0	Mbps
LTE	0	Mbps		0	Mbps
Peak	0	Mbps	Peak	0	Mbps
Avg	0	Mbps	Avg	0	Mbps
5GNR	1695	Mbps		1	Mbps
Peak	1695	Mbps	Peak	1	Mbps
Avg	534	Mbps	Avg	0	Mbps

		PCell	SCell1	SCell2	SCell3
LTE	Serving PCI				
	EARFCN				
	Band				
	RSRP(dBm)				
	RSRQ(dB)				
	SINR(dB)				
	DL TP(Mbps)				
	UL TP(Mbps)				
5GNR	Serving PCI	338	365	11	338
	NR-ARFCN(Band)	520110(41)	126270(71)	397470(25)	512190(41)
	SS-RSRP(dBm)	-54.91	-48.59	-62.41	-57.84
	SINR(dB)	34.06	29.90	28.22	38.49
	DL TP(Mbps)	954.79	134.51	120.01	485.21
	DL RB Num(Inc.0)	177.49	67.96	73.71	69.99

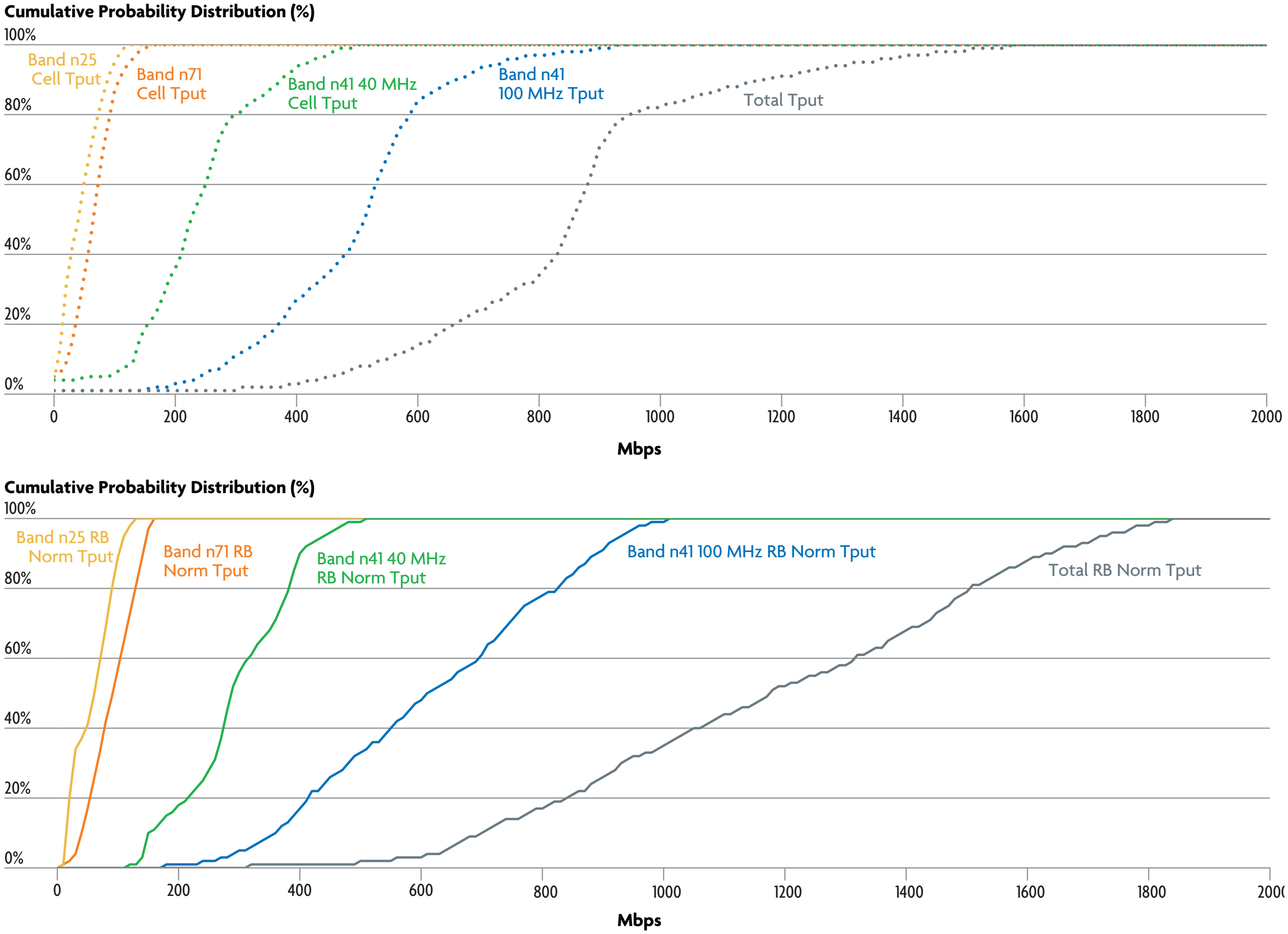
Source: Accuver Americas

Supplemental Test Results

The figures in this section provide background information which support some of the higher-level figures shown in the main body of the report. In Figure 2, we showed the mobile test device throughput at the 10th percentile during a drive test in a T-Mobile commercial cluster of 4CC sites. Figure 13 provides additional information on the results from that drive test. It shows the cumulative distribution of each component carrier as well as the total throughput, or the combined contribution from the four 5G carriers. The top figure shows the measured throughput and the bottom figure shows the RB normalized throughput, or the estimated throughput the mobile test device would have achieved it the network had allocated it all possible resource blocks (RBs) in each component carrier.

Given the big disparity in channel bandwidths between the two mid-band 5G carriers and the two low-band 5G carriers, it isn't surprising to see such a big gap between the two pairs of results. The key point, however, is that by leveraging all four component carriers, instead of a single 5G carrier, the total throughput was much greater than it otherwise would have been. This outcome was most important with lower Band n41 data speeds, which likely occurred when there were poor RF conditions, such as at cell edge.

Figure 13. Throughput Distribution by Component Carrier – Mobile Test Device with 4CC capabilities

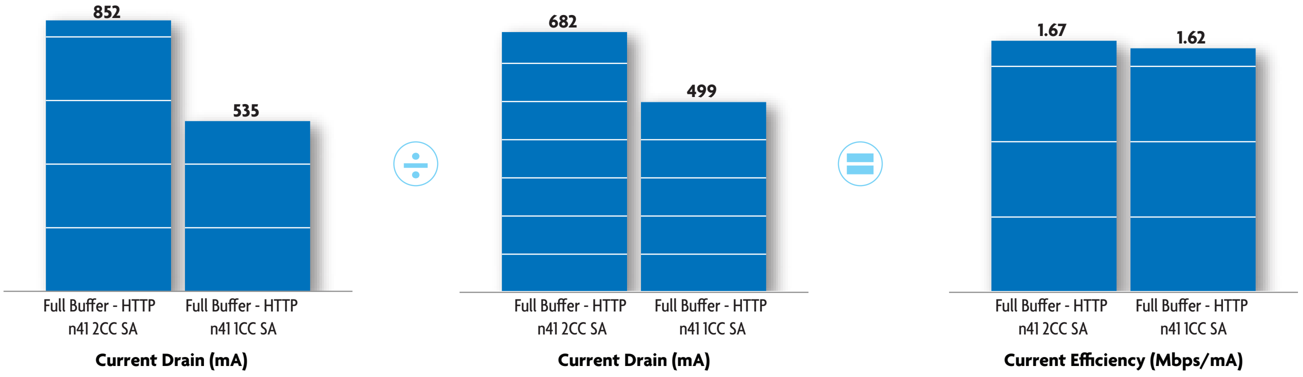


Source: Signals Research Group

We've developed an indirect means of measuring current efficiency that we have used in numerous studies in the past. When a smartphone is plugged into a notebook computer to capture chipset data, it is receiving a slow charge over the USB cable. This action negates the usefulness of third-party tools that can report the instantaneous battery drain of the smartphone, as reported by the Android operating system. As a workaround, we leverage application layer throughput which is measured and captured by Umetrix Data, both on the smartphone as well as on the Umetrix Data server. Since we are using application layer throughput in our analysis, we do not need to connect the phone to the computer. We do, however, use XCAL5 to capture RF conditions and how the network is allocating network resources (bands and RBs) in advance of doing the current measurement tests. This information provides us with additional insight when analyzing the data.

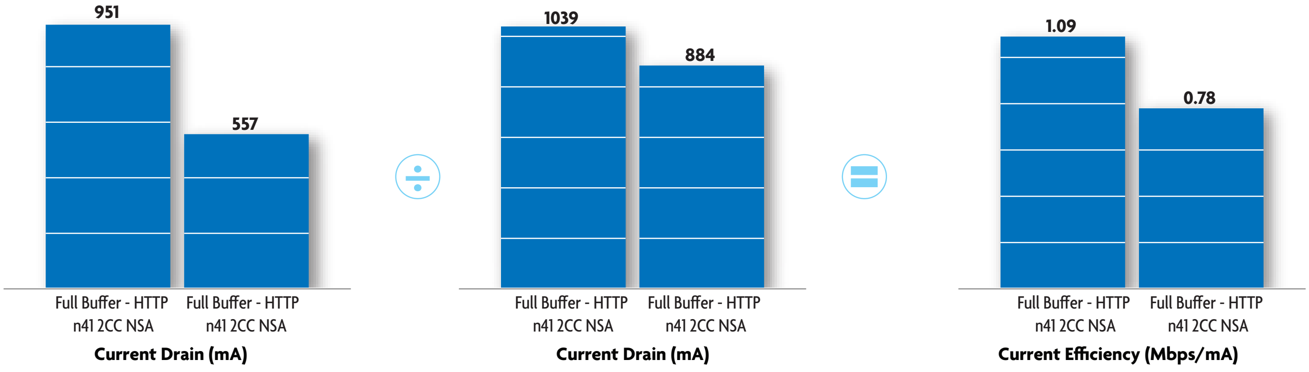
For this study, we conducted each current measurement test twice and then averaged the two results. We did these tests with a Galaxy S22 smartphone that was limited to 2CC functionality since we felt the mobile test device wasn't optimized for energy efficiency. With T-Mobile's support, we repeated these tests with Band n41 carrier functionality disabled at the cell site. Lastly, for both 2CC and 1CC network configurations, we did the tests with the smartphone configured to support NSA (LTE + 5G) and SA (5G only). Figure 14 shows three groups of figures for the SA mode of operation. The figure on the left shows the average application layer from two downlink data transfer tests, the middle figure provides the average current consumption (mA/H) for the two tests, and the figure on the right shows the current efficiency. As illustrated in the figure, the current efficiency represents the average throughput divided by the average current consumption. Figure 15 shows similar information for NSA mode.

Figure 14. 5G 2CC versus 5G 1CC Results – SA Mode



Source: Signals Research Group

Figure 15. 5G 2CC versus 5G 1CC Results – NSA Mode



Source: Signals Research Group

In both groups of figures, two expected outcomes occurred. The downlink data speeds were higher with 2CC than with 1CC for both SA and NSA. Likewise, the current drain was lower with 1CC than it was for 2CC for both SA and NSA. However, the higher current drain associated with 5G 2CC was more than offset by the higher downlink data speeds associated with the use of a second 5G carrier. It is our expectation that a commercial smartphone with 4CC functionality will achieve better current efficiency than 2CC, just as our test results showed the smartphone had higher current efficiency with 2CC than 1CC.

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