July 10, 2023

SiGNALS Flash!

Dispatches from the frontier of wireless

IT'S GETTING HOT IN HERE, SO...

SiGNALS Research Group
www.signalsresearch.com

EXECUTIVE SUMMARY

Since the launch of the first 5G networks back in 2019, we've done a lot of research on the implications of 5G on the temperature of the smartphone and its battery life. In our benchmark study of the 5G mid-band network in South Korea (SA 07/03/19, "K-POP Meets 5G (the crossover edition)") we wrote about the frequency of 5G RLFs (radio link failures) and how many of them were due to the 5G smartphone getting too hot. Conversely, we also wrote in another early 5G benchmark study (SA 08/19/19 "Strange Bedfellows") that while RLF due to thermal-related issues was a real problem, many of the earlier issues with 5G mmWave performance and reliability had nothing to do with thermal. Instead, incomplete mappings of LTE anchor cells and 5G mmWave sites caused the 5G mmWave connection to "disappear" even when standing close to the serving 5G mmWave radio. In other controlled studies we also showed that good old Mother Earth and the sun overhead had a far greater impact on the smartphone's temperature than 5G data consumption.

Over the years, we've also done several reports that looked at the relationships between 5G usage and battery life. Yes, 5G usage can kill the battery but it generally happens after consuming lots and lots of data. Once you equate data speeds, data usage and battery life, the real outcome is that faster data speeds almost always result in improved current efficiency, or the achieved data speed relative to the associated battery drain required to achieve that speed (Mbps/mA). This statement is true even though the current drain was almost always higher / much higher with 5G mmWave than it was with LTE. Most recently, we proved this point, along with analyzing many unrelated performance attributes, in two Signals Ahead reports: downlink – (SA 10/31/22, "Cage Match (FR2 in the Wild!)") and uplink – (SA 05/10/23, "Up – a benchmark study of 5G mmWave 4CC Uplink Performance"). It is only when 5G, and especially 5G mmWave, gets used for low bit rate applications that the inefficiencies emerge.

In this Signals Flash! we provide some results from a study that we did in collaboration with Rohde & Schwarz, which looks at the thermal characteristics associated with the baseband modems from some of today's 5G smartphones. As always, unlike our subscription-based Signals Ahead reports, you may forward this Signals Flash! report to whomever you want.

We did this study in collaboration with Rohde & Schwarz.

More is Less. Although 5G mmWave phones tend to get hotter faster with more component carriers (CCs) and with higher MCS allocations, the subsequent higher data speeds more than offset the rate of increase in the temperature. Case in point, with one smartphone we tested, the temperature delta after downloading 1GB of data was 7.8x higher when downloading at ~72 Mbps (1CC and MCS 5) than at ~2,100 Mbps (8CC and MCS 16), even though the latter configuration increased the modem temperature 3.6x faster than the 72 Mbps scenario.

Results May Vary. Just like the diet plans advertised on TV, there are performance differences across smartphones. For the same MCS and number of component carriers, we documented up to a 2-3x difference across the phones in the rate the temperature increased. Further, there was up to an 18 C delta in the maximum temperature the smartphones reached before shutting down the 5G radio.

Differing Strategies. Although we don't specifically analyze this point in this report, we observed differences in how smartphones dealt with thermal issues. Some smartphones "go for broke" until the phone thermals, while other smartphones back off on 5G data throughput / number of concurrent component carriers when the temperature rises too much.

COMING SOON!
5G: The Greatest Show on Earth!
VOLUME 34: UP
A BENCHMARK STUDY OF 5G UPLINK CARRIER AGGREGATION USING N25 (FDD) AND N41 (TDD)
PART OF “THE MOTHER OF ALL NETWORK BENCHMARK TESTS” SERIES OF REPORTS

Index of Figures


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5G: The Greatest Show on Earth!
VOL 33: MU-MIMO AND THE TOWER OF POWER
CHAPTER 2: THE PERFECT PAIRING WITH [BARBEQUE] PORK PARADOX
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Although 99% of the lyrics and the companion music video suggest otherwise, we're convinced that when the rapper Nelly penned the song "Hot in Herre" he based the song on his experiences with his mobile phone becoming too hot to handle. Our only uncertainty on this conclusion is that the song was released in 2002, or back in the day when the top-selling phone was either the Motorola Razr, a Nokia phone, or perhaps a BlackBerry. Adding to the uncertainty, if he was complaining about his mobile phone overheating then it would have been in the context of 3G and not a 5G smartphone, which got introduced nearly two decades later. Then again, we still remember the "hot" 3G smartphones on display at MWC, back when Cannes, France was large enough to host the festivities.

In any event, it should already be crystal clear that the topic of this Signals Flash is 5G thermal, or the situation in which a 5G smartphone either shuts down its 5G radio or backs off on how much data it requests over the 5G radio bearer to prevent a 5G radio link failure (RLF) due to excessive heat from occurring. The latter situation can occur if the smartphone stops using one or multiple 5G radio bearers, as could be the case with 5G mmWave, which today supports up to 8x100 MHz of spectrum. And while we didn't specifically include current consumption in this study, we know that a smartphone that gets hotter faster is also consuming more energy, meaning higher current consumption and a shorter battery life.

Table 1. Test Methodology Key Highlights

LTE Parameters	5G Parameters
Band 2	n260/n261
Downlink Power = -45 dBm	Downlink Power = -45 dBm
Bandwidth = 20 MHz	Bandwidth = 100 MHz (TDD)
MIMO: 4x4	TDD Pattern: 8 DL / 1 UL Slot
Downlink MCS = 26	MIMO: 2x2
Uplink MCS = 10	Downlink DCI Format: DCI 1_1
Downlink Transmission Mode: TM3	Uplink DCI Format: DCI 0_1
	DL/UL Aggregation Level: 2
	DL/UL RB Allocation: 66
	Downlink MCS: multiple fixed values, based on 64QAM table

Source: Rohde & Schwarz and SRG


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A BENCHMARK STUDY OF 5G mmWAVE
FOUR COMPONENT CARRIER UPLINK PERFORMANCE
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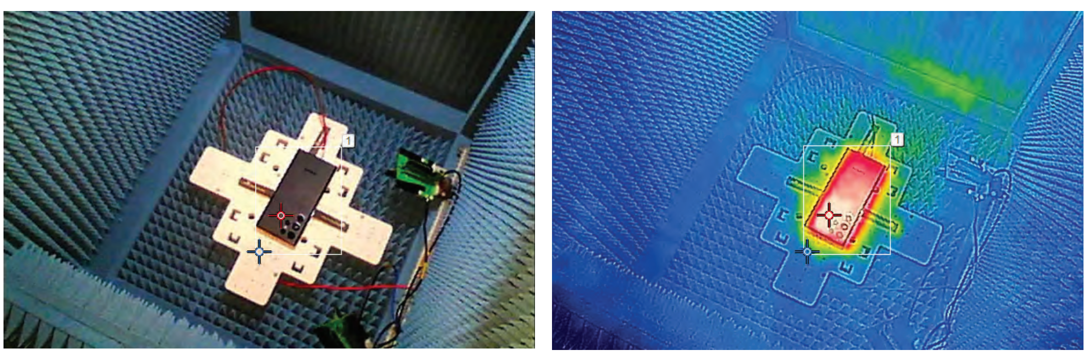
We collaborated with Rohde & Schwarz on this study. Testing took place at the R&S facilities in Coppell, Texas using the company's CMX500 5G One-Box Signaling Tester to generate the various RF conditions that were a part of the study. Each smartphone was tested in the ATS800R rack-mountable Compact Antenna Test Range (CATR) chamber. The device placement within the chamber's quiet zone was optimized for maximum performance based on initial measurement reports provided by the device under test. Each test involved transferring data to the smartphone with a fixed MCS (Modulation and Coding Scheme) that was set to be much lower than necessary relative to the RF conditions within the enclosed chamber. In other words, the tests weren't so much about RF performance (e.g., throughput) with strenuous conditions, but how the phone performed with the fixed MCS over an extended time period (from start until thermal failure). Ultimately, the measured throughput factored into the analysis, but only tangentially when equating the rise in temperature to the associated amount of transferred data.

R&S used a FLIR camera to measure and record the smartphone's temperature during the tests along with capturing other performance parameters with the CMX500. For purposes of our analysis, we focused on the maximum temperature the camera measured since the location of the highest temperature corresponded with the location of the 5G mmWave modem. As a side note, when we have done similar studies in the past, we relied on the battery temperature, as reported by the Android operating system. The battery temperature determines when to invoke a 5G thermal RLF (Radio Link Failure) with the temperature sensors near the battery likely recording temperatures that are lower than observed at the modem.

Figure 1 shows two images of a smartphone within the anechoic chamber that were taken with the camera. We've labeled the two figures by paying homage to the 1980s PSA (Public Service Announcement).

Figure 1. Data Capture Methodology

This is Your Smartphone ***This is your Smartphone on 5G mmWave***



Source: Rohde & Schwarz and Signals Research Group

In this *Signals Flash* we include a range of data sets. Some results provide a high-level indication of performance and how it varied between smartphones or with different RF configurations / settings for the same smartphone. Other results provide supporting information to validate and add credibility to the information contained in the high-level figures. Put more succinctly, we have a lot of data to back up our conclusions and we're providing only some of it in this report.

Measured throughput did vary modestly between the smartphones, but not enough to warrant a discussion.

We're including results from five smartphones in this study. Since we believe that some of the results are a bit dated and there are now new 5G modems in the market, we are refraining from disclosing the smartphone models we tested as well as information about the 5G components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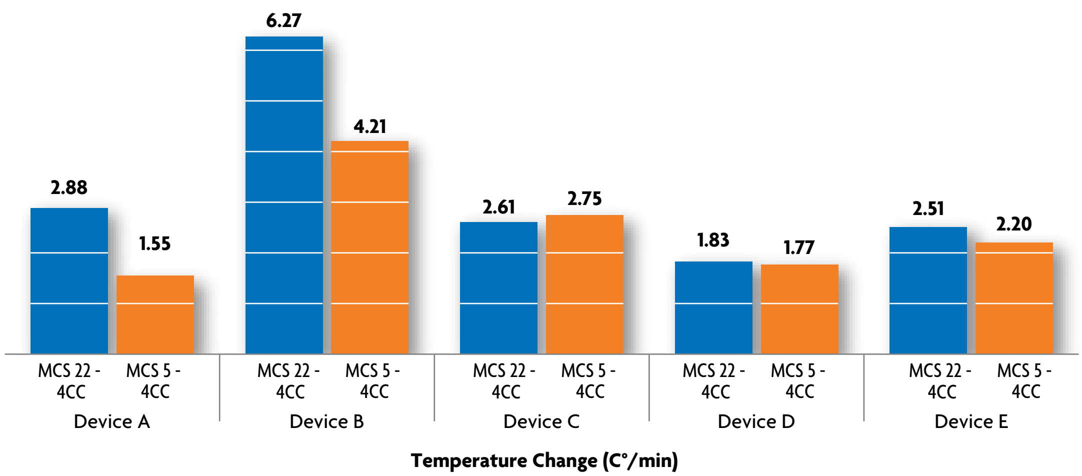
used in each smartphone. Figure 2 shows the average temperature change (C°/min) for each smartphone with two vastly different scenarios: 4 component carriers (4CC) with MCS 22 and 4CC with MCS 5. With both scenarios we locked the MCS to the target MCS with RF conditions that were more than adequate to support the data transfer. Although this information isn't included in this report, 4CC and MCS 22 equates to an RLC layer throughput of approximately 1.5 Gbps and 4CC with MCS 5 delivers an RLC layer throughput of approximately 333 Mbps. Measured throughput did vary modestly between the smartphones at both the physical and RLC layers, but not enough to warrant a discussion, especially given the primary objectives of this study.

Given the associated data speeds, it isn't surprising that the temperature increased faster with 4CC MCS 22 than it did with 4CC MCS 5. It is noteworthy that the differences in the temperature gradient were relatively modest, compared with the differences in the data throughput – something we quantify in this report. The other noteworthy data point is the results varied quite significantly across smartphones, especially with Device B. With 4CC and MCS 22 there was a 3.4x difference between the slowest heating phone and the fastest heating phone while with 4CC and MCS 5 the difference was 2.7x.

Figure 2. Comparative Results by Smartphone

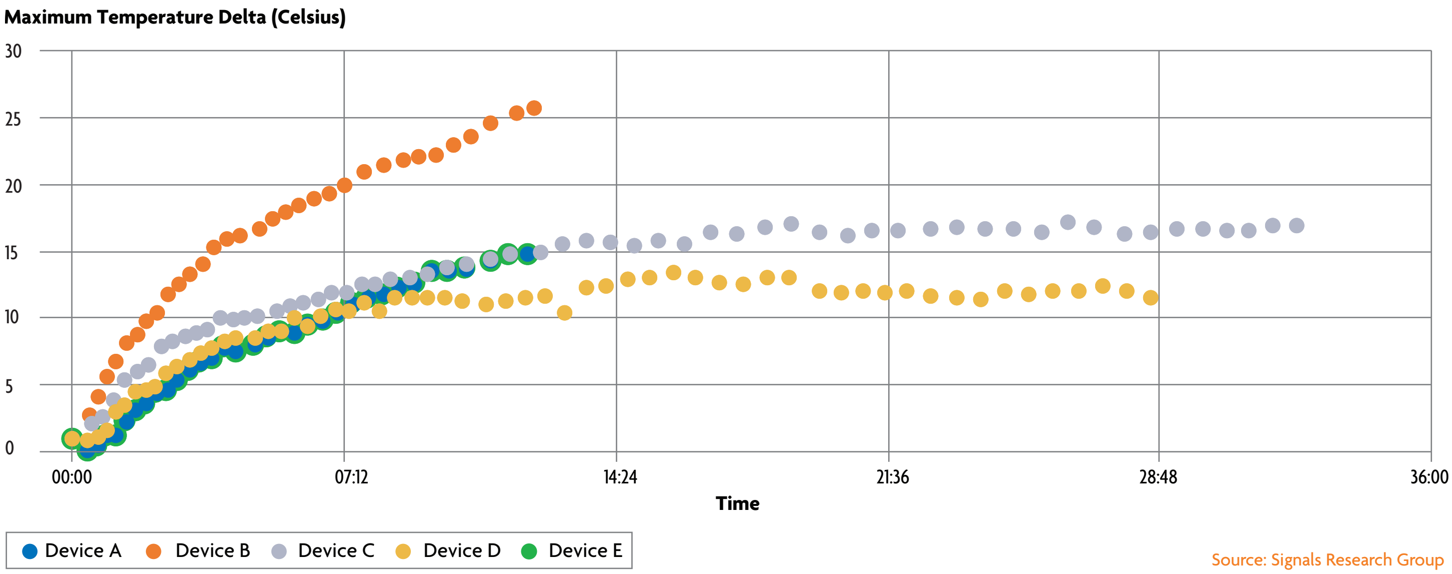


Source: Signals Research Group

Figure 3 (MCS 5 and 4CC, or ~310 Mbps) and Figure 4 (MCS 22 and 4CC, or ~1.5 Gbps) provide scatter plots that show the measured temperature of the baseband modem / hottest spot on the smartphone at various measurement points during the tests. In each figure, the data points stop for each smartphone when it reached its thermal temperature, implying that some smartphones reached their thermal limit much quicker than other smartphones. The deceleration of the temperature increase that is apparent with some phones was due to various thermal mitigation techniques used by the smartphones – for example, dropping one or more component carriers, which subsequently reduced the 5G mmWave data speeds. For purposes of the information shown in Figure 2, we used data points from the first ~2 minutes of each test, or well before the smartphones invoked their various thermal mitigation techniques.

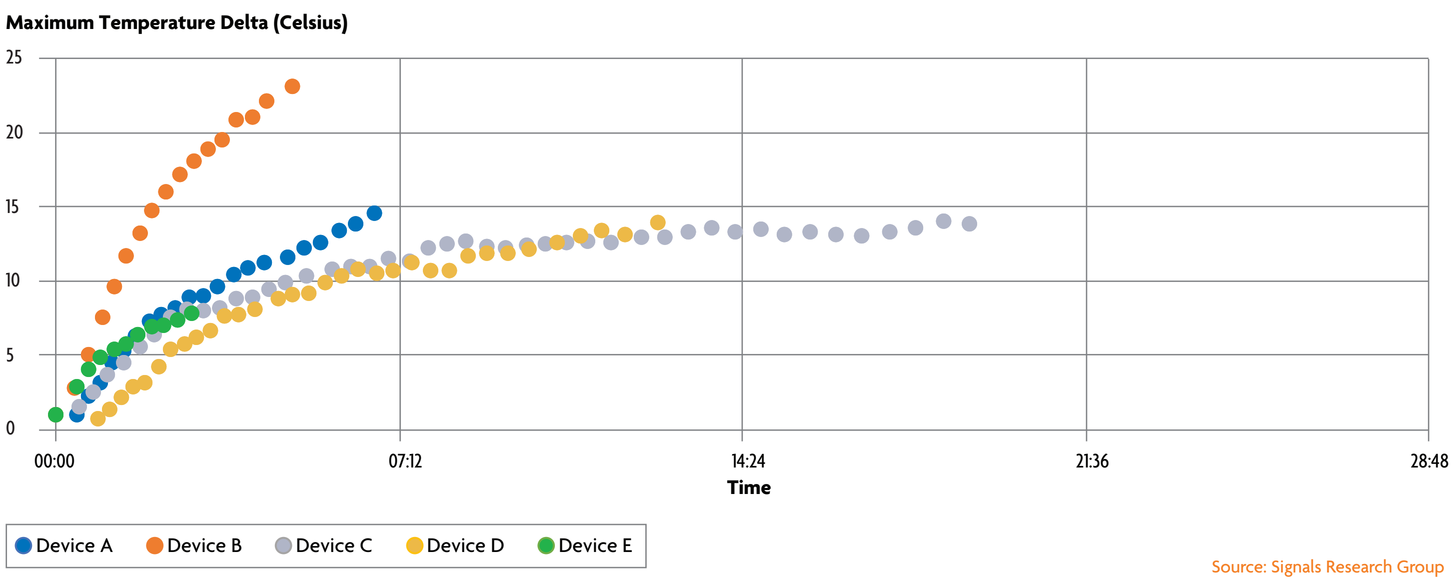
The deceleration of the temperature increase that is apparent with some phones was due to various thermal mitigation techniques used by the smartphones.

Figure 3. Maximum Temperature Measurement Versus Time – MCS 5 and 4CC



Source: Signals Research Group

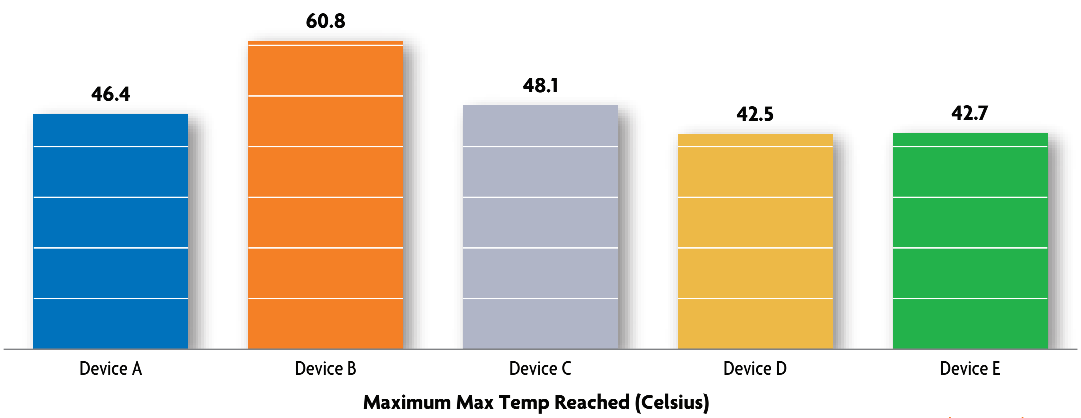
Figure 4. Maximum Temperature Measurement Versus Time – MCS 22 and 4CC



Source: Signals Research Group

Figure 5 shows the maximum temperature we measured on each smartphone during the 4CC MCS 22 test. This temperature indicates the point when the smartphone stopped using 5G mmWave. This figure, and the earlier figures, indicate that some smartphones get hotter far faster than other smartphones and that some smartphones greatly pushed the limit in terms of how hot they were allowed to operate. We suspect that the location of the 5G modem relative to the temperature sensors near the battery is one good explanation why some phones were able to get hotter than other smartphones.

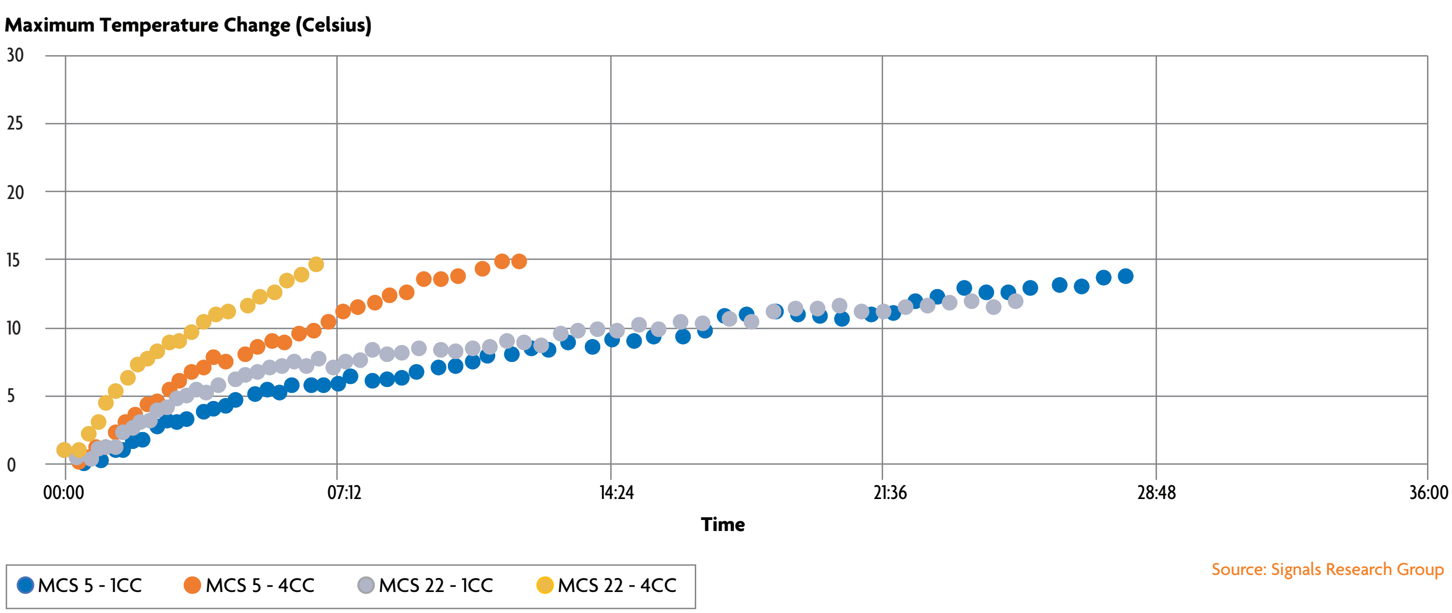
Figure 5. 5G Thermal Temperature by Smartphone



Source: Signals Research Group

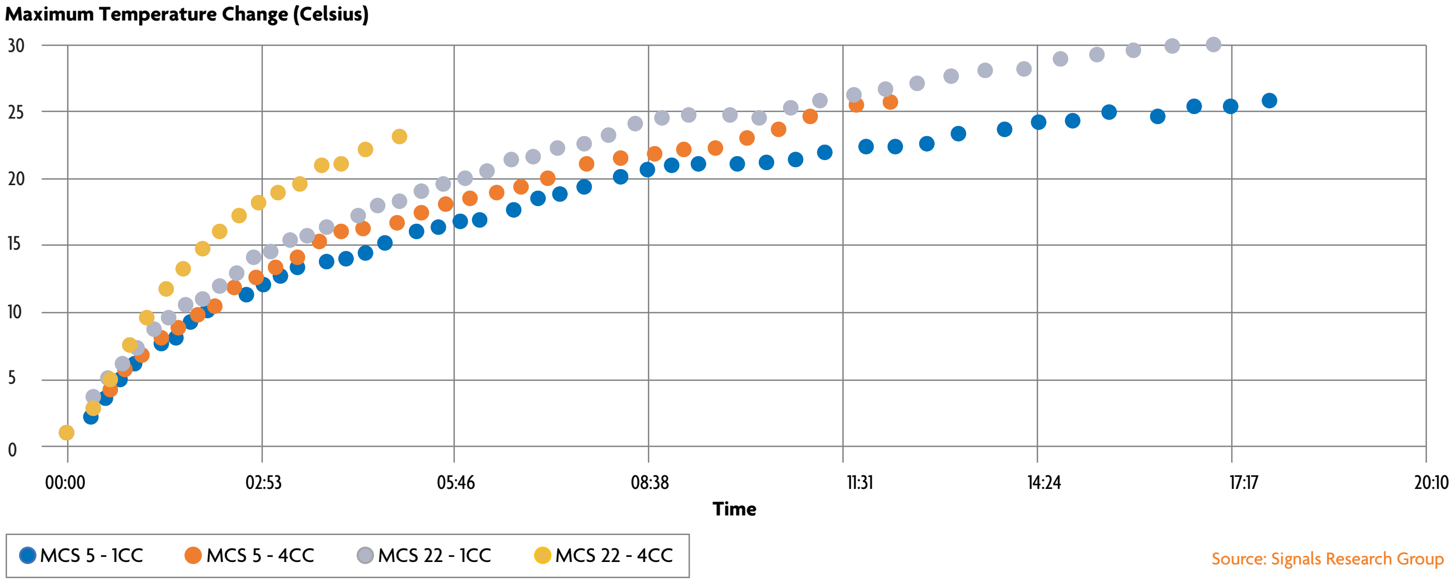
The next three figures show how the maximum temperature measured on the smartphone increased during the test. Each figure shows results for four tests involving 1CC and 4CC, as well as MCS 5 and MCS 22. Although we kept the Y axis scale the same on each figure, there are differences in the X axis (time) with a longer time scale indicating the thermal occurred later in the test. As with the earlier figures, the reduced gradient in the temperature deltas was generally due to various thermal mitigation techniques. For our analysis of the data, we focused on the first few minutes of the tests or prior to the smartphones implementing these various mechanisms.

Figure 6. Device A Maximum Temperature Delta – by Component Carrier Count and MCS



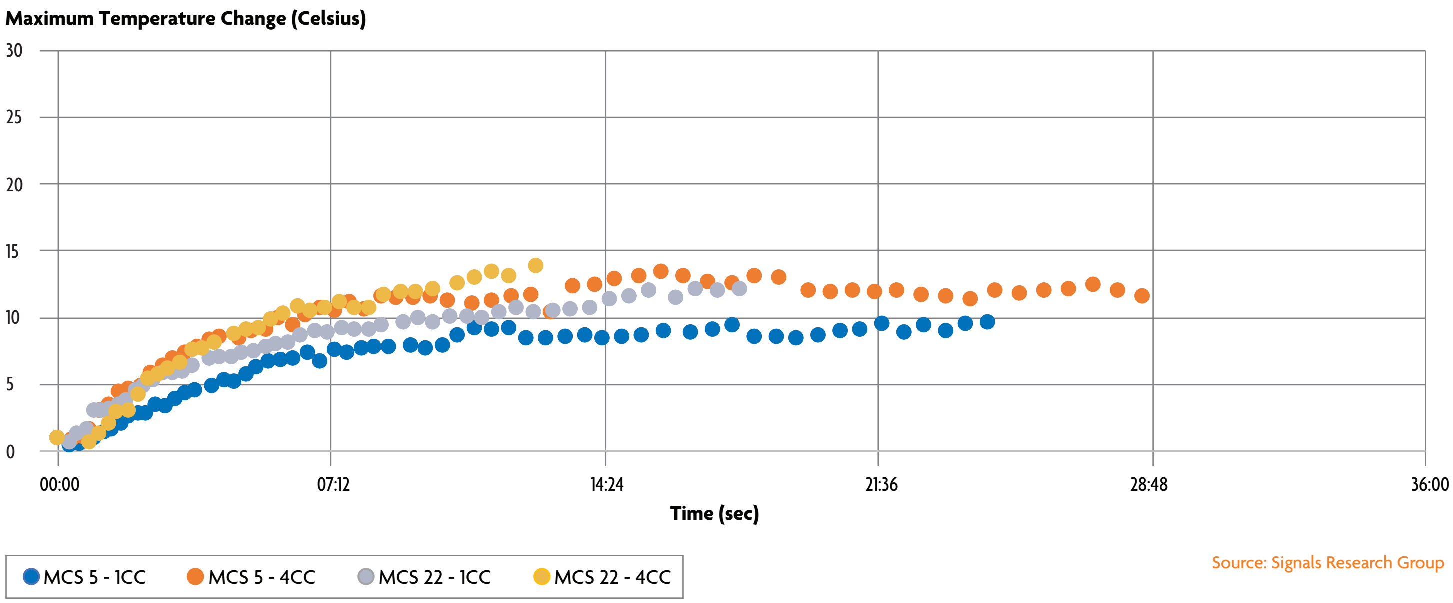
Source: Signals Research Group

Figure 7. Device B Maximum Temperature Delta – by Component Carrier Count and MCS



Source: Signals Research Group

Figure 8. Device C Maximum Temperature Delta – by Component Carrier Count and MCS

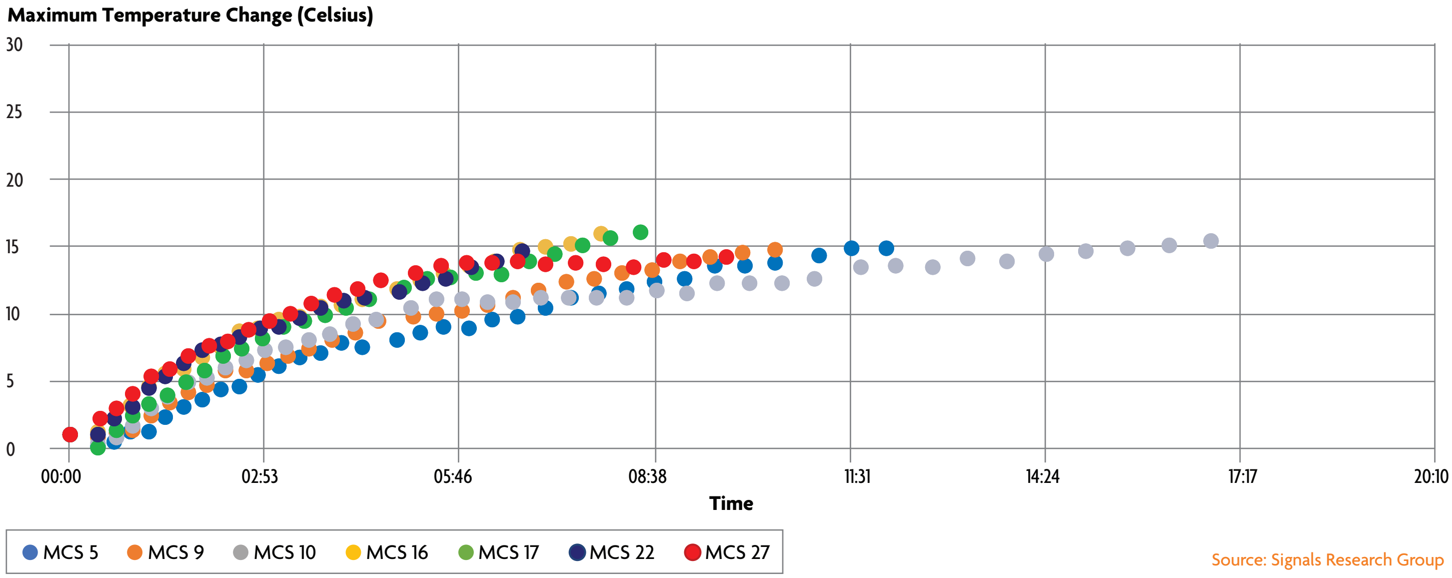


Source: Signals Research Group

The next four figures show the change in the maximum temperature with the smartphones operating in 4CC mode with the various fixed MCS allocations. We had some issues getting certain smartphones to work with MCS 27 (likely interoperability related) so some figures do not show results for all potential MCS values that we included in the study. With the four smartphones shown in these figures, the temperature increased faster with the higher MCS values, which is expected. The point, however, is that the more rapid increase in temperature also corresponded with much faster data speeds, meaning that when downloading a fixed amount of data, the absolute increase in temperature was almost always lower when the smartphone was downloading at a faster speed. This statement is true even though the smartphones also experienced a more rapid increase in temperature when downloading at faster speeds.

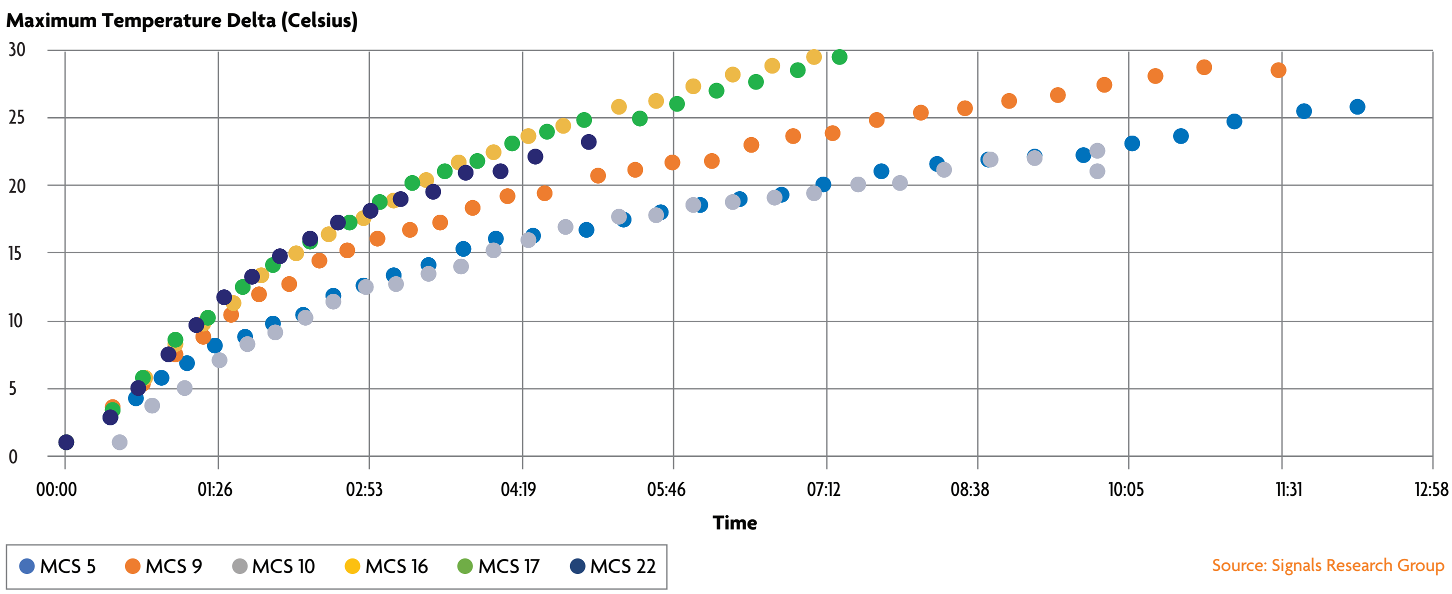
The absolute increase in temperature was almost always lower when the smartphone was downloading at a faster speed.

Figure 9. Device A Maximum Temperature Delta versus Time with 4CC – by MCS



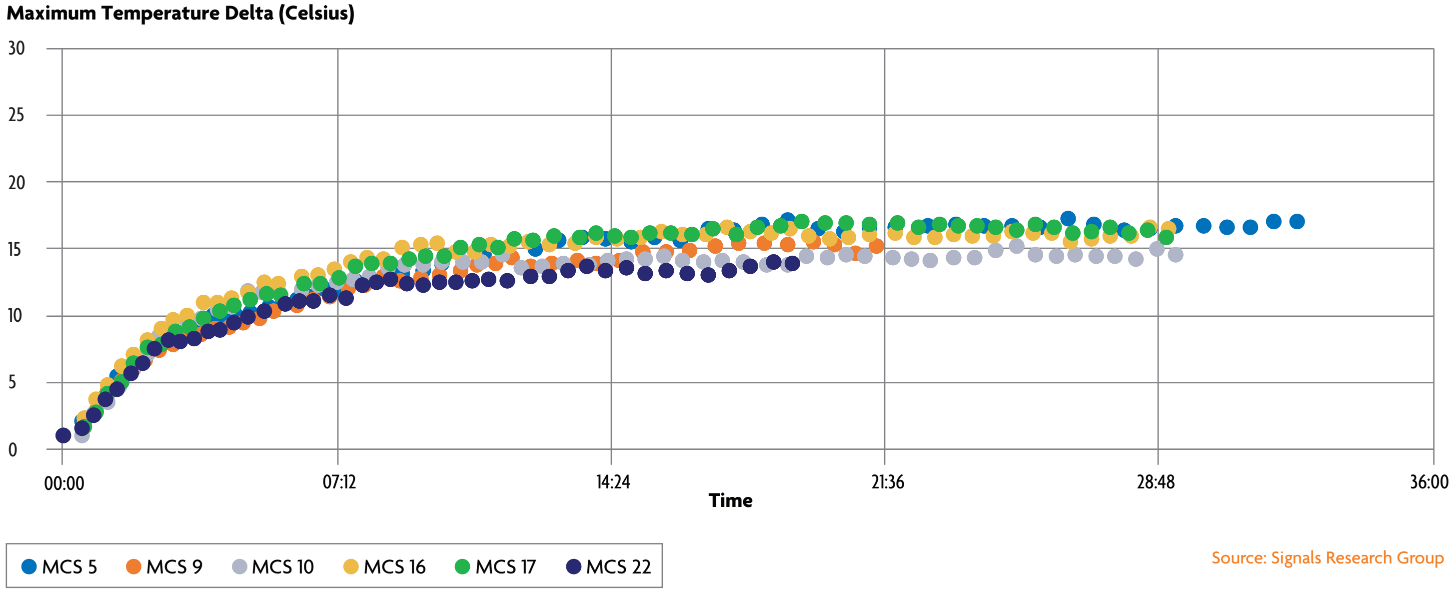
Source: Signals Research Group

Figure 10. Device B Maximum Temperature Delta versus Time with 4CC – by MCS



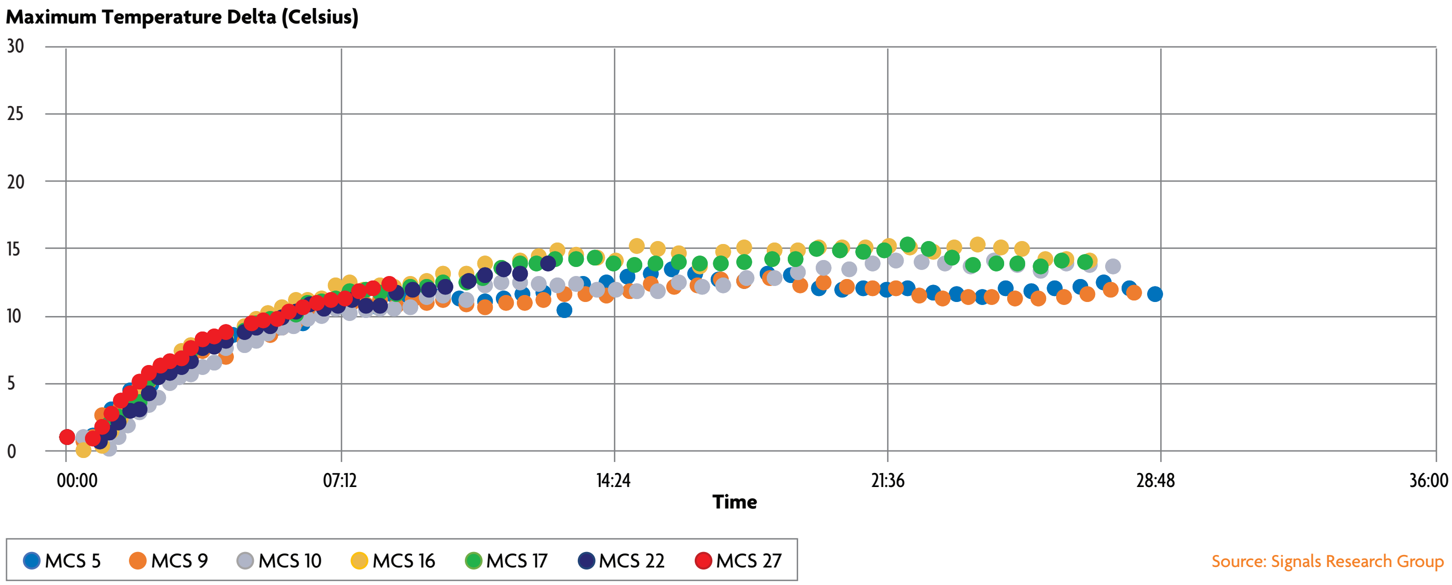
Source: Signals Research Group

Figure 11. Device C Maximum Temperature Delta versus Time with 4CC – by MCS



Source: Signals Research Group

Figure 12. Device D Maximum Temperature Delta versus Time with 4CC – by MCS



Source: Signals Research Group

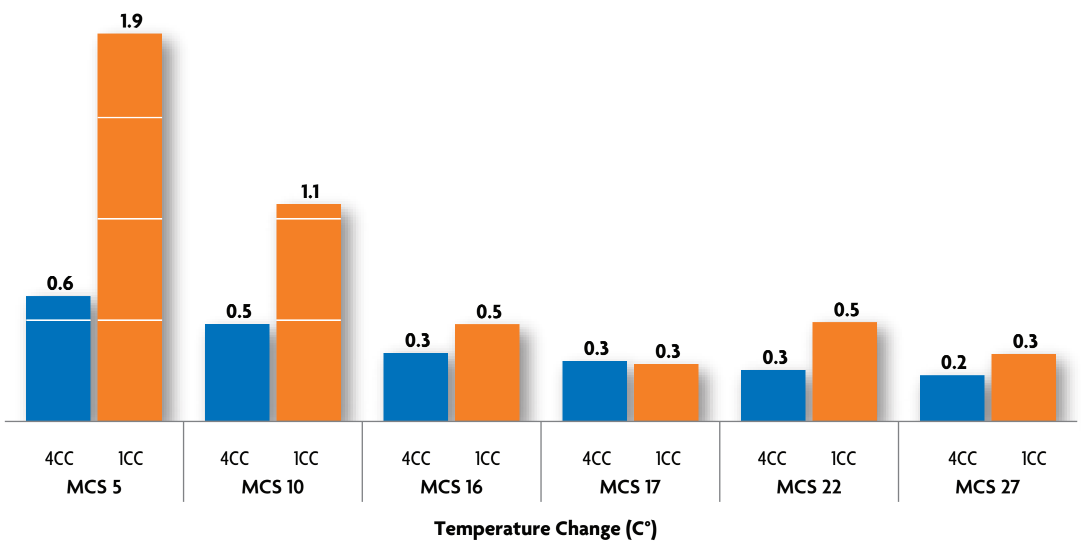
The results in Figure 13 demonstrate this point. The figure, which is specific to Device A, shows the increase in temperature associated with downloading a 1GB file using one of six different MCS values along with 1CC and 4CC configurations. For this analysis, we used actual throughput results that we measured as part of the study. Two observations are worth pointing out:

1) The temperature delta was much higher with 1CC than with 4CC.

2) The temperature delta was much higher with lower MCS than with higher MCS.

The figure does show modest nuances which contradict these two statements. For example, the increase in temperature with 1CC MCS 22 was higher than it was with 1CC MCS 17; however, we attribute this outcome to some inaccuracies when measuring the temperature. We didn't measure current consumption as part of this study but since heat equates to energy consumption, we are most certain that a smartphone with a higher increase in its temperature gradient was also consuming more energy, meaning a shorter battery life.

Figure 13. Device A Maximum Temperature Increase with 1GB Data Transfer – by Component Carrier Count and MCS

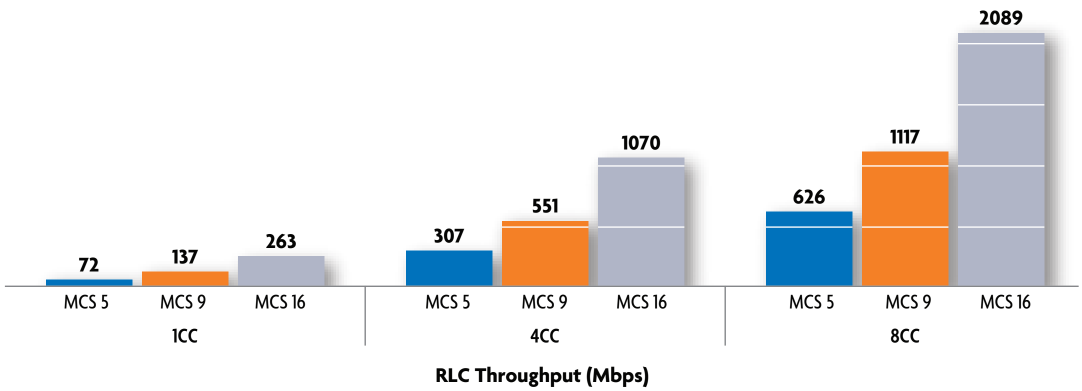


Source: Signals Research Group

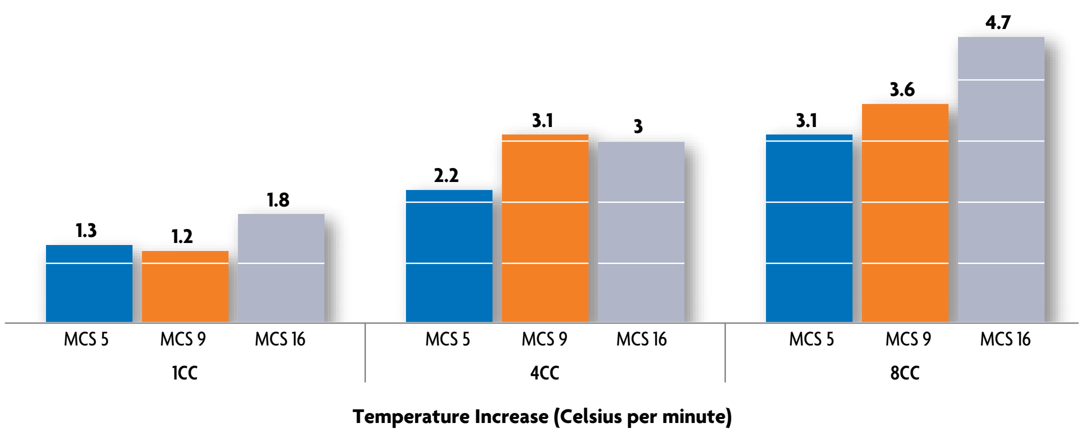
Finally, Figure 14 provides some background data points for Device E with various tests that we conducted. The top illustration includes the measured RLC throughput with 1CC, 4CC, and 8CC configurations along with three different MCS values. The middle illustration shows how the smartphone's temperature increased with the measured data speeds. Finally, the bottom figure shows the total increase in temperature associated with the aforementioned data speeds and temperature gradients while downloading a 1GB data file.

Figure 14. Device E Maximum Temperature Increase with 1GB Data Transfer – by Component Carrier Count and MCS

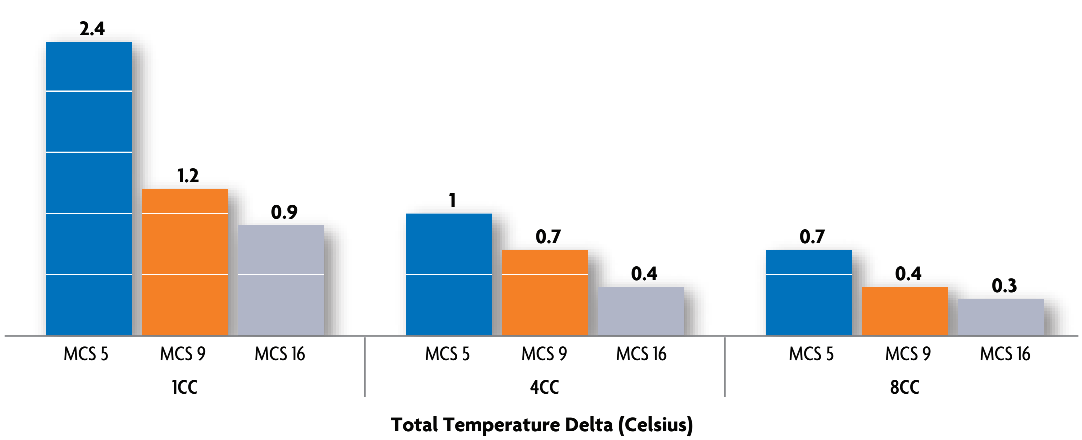
RLC Throughput



Temperature Rate Increase



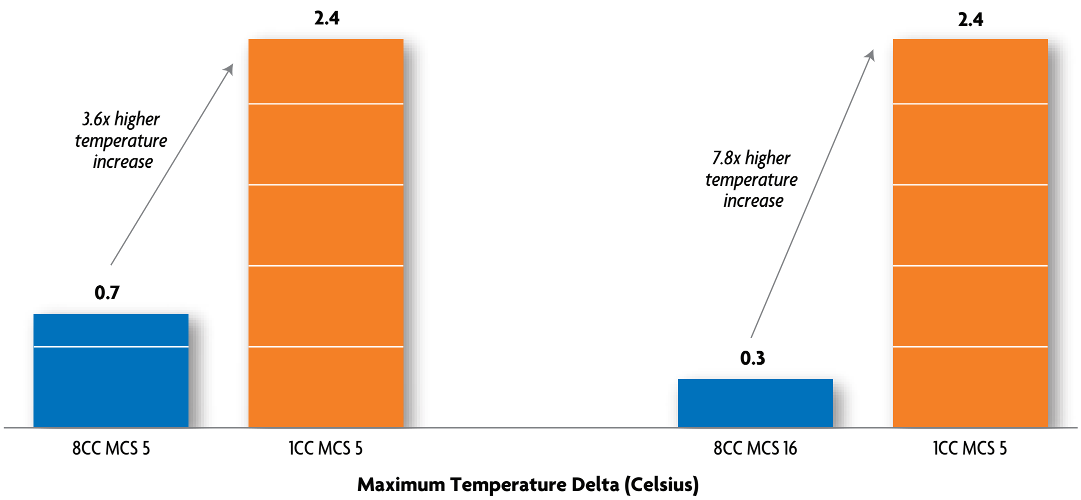
Total Temperature Increase with 1GB Data Transfer



Source: Signals Research Group

Finally, the information in Figure 15 highlights data points within Figure 14. Namely, this smartphone's 5G modem experienced a 3.6x higher increase in its temperature while downloading a 1GB file using 1CC and MCS 5 (~72 Mbps), compared with using 8CC and MCS 5 (~626 Mbps). Likewise, the delta was 7.8x between a smartphone using 1CC MCS 5 and 8CC MCS 16 (~2.1 Gbps). It pays to be fast!

Figure 15. Device E Comparative Results – 1CC versus 8CC



Source: Signals Research Group

IN CASE YOU MISSED IT:
SIGNALS AHEAD BACK ISSUES

➤ **6/28/23 "5G: THE GREATEST SHOW ON EARTH! MU-MIMO and the Tower of Power (Chapter 2)"** SRG just completed its 33rd 5G benchmark study. For this endeavor we collaborated with Accuver Americas and Spirent Communications to conduct an independent benchmark study of 5G MU-MIMO, using Verizon's commercial 5G network in Memphis, TN, where Samsung is the RAN infrastructure supplier.

Highlights of the Report include the following:

Our Thanks. We did this study in collaboration with Accuver Americas (XCAL5 and XCAP) and Spirent Communications (Umetrix Data). SRG is responsible for the data collection and all analysis and commentary provided in this report.

Our Methodology. We primarily tested at one cell site (3 sectors) which supported MU-MIMO, 100 MHz channel bandwidth (versus the typical 60 MHz that VZ has deployed), and 10 Gbps backhaul. We did stationary testing with four Galaxy S22 smartphones placed in vehicles in various locations within the sector and included 2 different drive test routes to gauge the impact of mobility on MU-MIMO and SRS performance. We estimate ~15 different device placements with stationary tests.

Key Differences. To our surprise, the virtualized RAN (vRAN) supported 16 downlink MIMO layers and 8 uplink MIMO layers. We didn't realize this capability until after we started analyzing the results in detail. We didn't test uplink MU-MIMO while with only 4 smartphones, the results we obtained likely understate the full MU-MIMO potential of the network.

The Results are In. Without getting into specifics, we observed near-perfect reuse of network resources (RBs) in most tests. Additionally, the aggregate MIMO layer count was frequently close to 8 layers across all smartphones after adjusting for RB use/reuse, and reaching at least 12 layers in some cases. Although MCS dropped in most tests, the net effect was still up to a high double-digit increase in sector capacity. The results with devices placed close together wasn't what we were hoping for since the sharp drop in MCS more than offset the high RB reuse and higher total MIMO layer count versus SU-MIMO.

FWA. FWA is THE use case for MU-MIMO. In addition to the need for increased low-cost capacity due to the usage profile of FWA, FWA benefits from relying on stationary devices (CPEs), which generally tends to result in better MU-MIMO results.

➤ **5/10/23 "5G: The Greatest Show on Earth! Vol 32: UP"** SRG just completed its 32nd 5G benchmark study. For this endeavor we collaborated with Accuver Americas and Spirent Communications to conduct an independent benchmark study of 5G mmWave 4 component carrier (4CC) uplink performance, using AT&T's commercial network in Glendale, AZ.

Highlights of the Report include the following:

Our Thanks. We did this study in collaboration with Accuver Americas (XCAL5/XCAL-Solo and XCAP) and Spirent Communications (Umetrix Data). SRG is responsible for the data collection and all analysis and commentary provided in this report.

Our Methodology. We tested within State Farm stadium and around the Glendale Entertainment District. Nokia [and some Corning] is the infrastructure supplier in this market. We used four flagship Samsung smartphones, from the Galaxy S23 back to the Galaxy S20 Plus. We used Umetrix Data to generate the uplink/downlink data transfers and XCAL-Solo to log the chipset data. We also used various Android applications to measure and record the battery current drain.

Temperamental. We can best describe the 4CC uplink performance as being temperamental. Although it was possible to obtain reasonably good performance when directly facing the serving cell, the uplink speeds were highly dependent on the phone's orientation to the serving site and body blockage. The variability in the uplink [and downlink] speeds was directly related to the signal strength (RSRP).

Battery Temperature. Despite our use of the ice cube bath, we found that high bandwidth downlink and uplink data transfers only had a modest impact on battery temperature. However, the glaring sun was a killer, meaning that a 5G smartphone could hit its thermal limit even before transferring a single byte of data over 5G. We quantify these comments.

Battery Current Drain. Once again, the higher the throughput the higher the current efficiency or the achieved throughput for a given amount of current (Mbps/mA). While it is true higher data speeds increase the battery current drain, it is more than offset by the increase in data speeds. The Galaxy S23 meaningfully outperformed the S20 Ultra and other legacy phones in this category.

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

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

Thematic Reports

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

Benchmark Studies

- *5G NR mmWave Fixed Wireless Access with IAB*
- *UL-MU-MIMO*
- *5G uplink CA benchmark study*
- *Open RAN network performance benchmark study 1 – Dish Network Revisit*
- *Open RAN network performance benchmark study 3 – Scheduling Efficiency*
- *FR1 + FR2 NR-DC network performance benchmark study*
- *MU-MIMO benchmark study, part III (FR1)*
- *SRS-based beamforming benchmark study*
- *DSS Update benchmark study*

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