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Author:
Wayne Lam

Criticality of 5G Modem to RF Integration

A look inside the latest smartphone design - Samsung's Galaxy S20 Ultra

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Wayne Lam, Principal Analyst, Mobile Devices

In this whitepaper, we will examine the progress made within the past year of a leading mobile 5G design as presented from the teardown analysis of Samsung Galaxy S20 series of smartphones. The cohesiveness of the modem-to-antenna design help illustrate the criticality of an integrated approach in 5G phones. This paper will address some of the following key points:

- Increasing design complexities in 5G modem and RF are driving OEMs adoption of integrated modem-to-RFFE solution in 2nd wave of 5G phones
- Phone SKUs with both 5G mmWave and sub-6 now prevalent and expected to become the norm for leading smartphone designs moving forward
- Significance of Samsung's decision to use the Qualcomm Snapdragon X55 Modem-RF System for its flagship phone design in Korea
- Key RF Front End design changes/enhancements that are required to support 5G standards especially for UHB Sub-6 GHz frequencies
- The importance of mmWave antenna module form factor to the overall design of 5G devices
- Providing handset OEMs capabilities to expand to other global markets despite the added 5G RFFE complexities of global 5G roaming support

In futurist Ray Kurzweil's book, *The Singularity is Near*, he makes an elegant point that technological advancements are coming at an ever-increasing pace. This exponential progress is plainly on display at the convergence of compute and communications. Whereas 4G LTE devices and adoption rates set records a decade ago; 5G deployment today - especially with hardware like modems - are progressing at an even higher rate. What took years to accomplish now takes months. As Kurzweil writes, "Evolution applies positive feedback, the more capable methods resulting from one stage of evolutionary progress are used to create the next stage." This is an apt description of the advancements in 5G modem and RF technologies.

Continued 5G Design Wins

For component manufacturers, winning a 1st generation design is a significant achievement. However, keeping the design slot as OEMs begin to manufacture at scale is an even bigger win. For the Galaxy S20 series, Samsung set the 5G design standard for 2nd generation 5G smartphone designs. While their marketing material may focus on the large immersive displays and 100-time camera zoom, it is the less prominent modem and RF technologies that goes largely un-noticed despite its significance.

For Qualcomm, 5G was an opportunity to grow its industry leadership and even branch out into adjacent markets. Having helped with the acceleration of 5G standards ratification, Qualcomm produced a complete suite of 5G components and ensured the availability of 5G phones at launch of 5G networks. Qualcomm's bold move led them to create a "modem-to-antenna" product offering which was both technologically vital for the success of 5G and an industry-disrupting move to crack into the RF components industry. By virtue of supporting four wireless generations, modern wireless modems are stacked with complexities of interoperations between 5G, 4G, 3G and 2G as well as those of WiFi, GPS, and others. To ensure that 5G "just works", Qualcomm took the initiative to not only supply the core silicon for mobile devices but a complete solution that includes RF Front End components like power amplifier modules, filters technology, antenna switches and envelope tracking. This helps mitigate the burden of complexity and integration for handset manufacturers.

Hardware Analysis

This whitepaper attempts to trace the evolution of 5G component design from the first generation to the latest 2nd generation of 5G smartphones. Having proven themselves quite capable with RFFE technology, especially for millimeter-wave on first generation 5G designs, Qualcomm has continued its success with 5G design wins in Samsung's flagship Galaxy S series. The choice to continue to use Qualcomm components by Samsung is a significant one since the Korean conglomerate also has 5G modem chipset capabilities and often source internally to strategically balance their supplier relationships. Here in the review of the Galaxy S20 Ultra, we will explore the impact of Qualcomm's second generation 5G modem-RF integrated system design by comparing and contrasting the evolution of progress and design changes from the previous Samsung 5G smartphone.

In order to perform a valid inter-generational 5G design comparison, it is crucial that we select a common OEM with similar feature sets spanning over 2 design cycles as the basis of our teardown analysis. In this case, the popular Samsung Galaxy S series was identified to highlight the 5G enhancements made within this period of time. The Samsung Galaxy S series of smartphones are especially useful for our analysis since the product is a flagship device which means that it is a design with the all the latest 5G technologies built in. For those reasons, the Samsung Galaxy S series is used as the basis of this whitepaper.

The entire 2020 Galaxy series from Samsung is 5G capable. This is an industry first meaning that there are no longer a 4G-specific SKUs being offered [as with Samsung's flagship line in 2019]. This industry acknowledgment of 5G as a pre-requisite for modern device designs speaks to the general confidence behind the new wireless technology.

Arguably the biggest change in Galaxy S series 5G design is the inclusion of both Sub-6 GHz and millimeter wave 5G within the same device – not an either/or design of the 1st generation. Of the 3 flagship designs in the Galaxy S series, two models (Galaxy S20+ and S20 Ultra) come standard with both sub-6 and mmWave. In South Korea, Samsung opting to stay with a Sub-6 GHz device while in the US, Verizon will be taking a mmWave version of the same phone. Where applicable, we will also look at and review the Korean market Galaxy S20 which is also powered by the Qualcomm Snapdragon X55 modem-RF system.

Samsung has been leaning on Qualcomm as a key supplier in their late-model 5G smartphones. Even within their own domestic market of South Korea, the entire Galaxy S20 line is using Qualcomm X55 modem-RF system - first for the Korean domestic market given Samsung's history of only including their own Exynos platform for the home market. Samsung's decision to use the Qualcomm platform is likely borne out of the realized benefits of having a tightly integrated 5G modem and RF Front End design. While Samsung continues to use Exynos designs in the European market, they have opted to use the Qualcomm platform especially in markets with complex 5G spectral holdings. The big selling point for the Qualcomm platform is having resolved the complications brought on by the myriad of global RFFE requirements.

Streamlining the Modem Silicon

The first generation 5G solution in the Samsung Galaxy S10 was based on Qualcomm's Snapdragon X50 Modem-RF System. This 1st Gen 5G modem was a 5G-only modem. That is to say, the Galaxy S10 relies on the main Snapdragon 855 SoC to perform the 4G/3G/2G functionalities. The 1st Gen Snapdragon X50 Modem-RF system is essentially a "bolt-on" 5G solution as the Snapdragon X50 modem connects to a 5G-specific RF transceiver and a 5G-specific RF path which is usually a single or dual band design with either Sub-6GHz or millimeter wave versions.

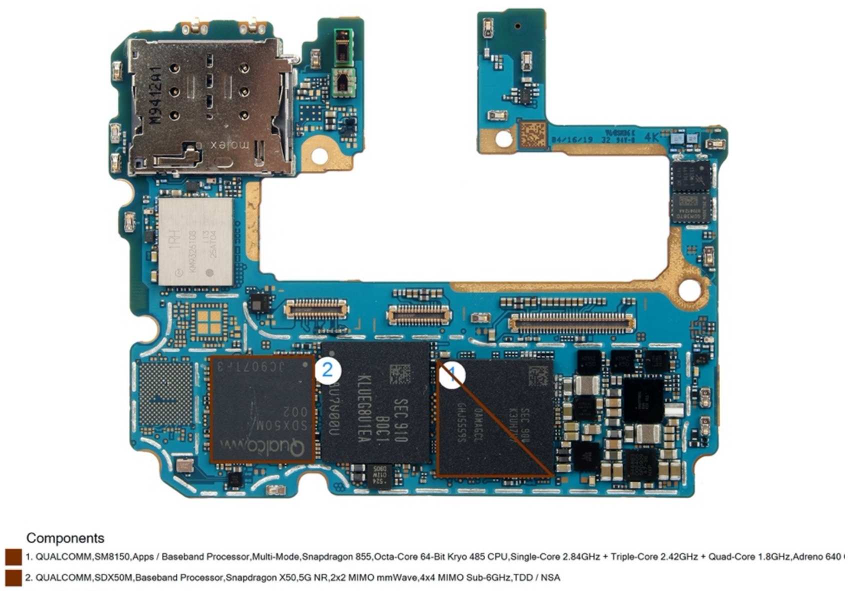

Figure 1: main PCB for Samsung Galaxy S10+ 5G

In the latest Samsung Galaxy S20 Ultra, the latest Qualcomm Snapdragon 865 platform design uses discrete modem and applications processor chips. Compared to the Snapdragon X50 Modem-RF system, the 5G and 4G-2G modem functionalities are combined into one single chip, the Snapdragon X55 modem now supports 5G/LTE as well as legacy standards. Also, unlike its predecessor, the Snapdragon X55 Modem-RF system is also linked to a common RF transceiver further reducing silicon count, power consumption and PCB footprint.

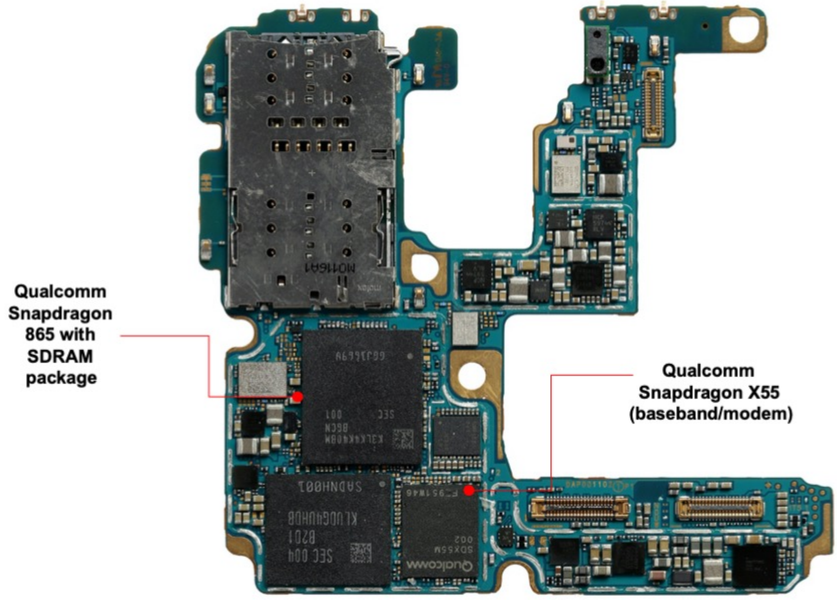

Figure 2: main PCB for Samsung Galaxy S20 Ultra designed with Qualcomm Snapdragon 865 modem-RF system

Within the Korean version of the Galaxy S20 (model SM-G988N), Samsung has leveraged the same streamlined 2nd Gen Qualcomm architecture. As the following graphic illustrates, the same Snapdragon 865 platform is used albeit in a different board layout.

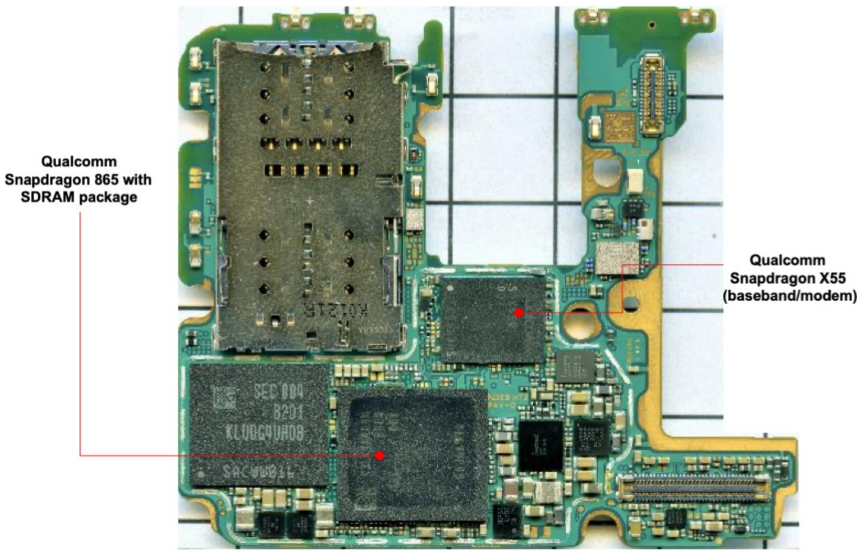

Figure 3: main PCB for Samsung Galaxy S20 model SM-G988N

Comparing to the 1st Gen design, the 2nd Gen Qualcomm design (Snapdragon 865 + X55 modem) reflects a “5G-first” electronic design. What “5G-first” means in this case is that 5G connectivity is the basis or starting point of smartphone design. By resolving the modem to RF complexity, Qualcomm offers OEMs the benefits of a fully vetted modem to RF system. Furthermore, by having one section of the smartphone design already completed, OEMs can better focus their internal engineering resources on other category-defining innovations. Ultimately, this decision to out-source the core electronics is likely due to Samsung's desire to simplify design complexities and allowing the Galaxy S20 series to globally get to market faster.

Taming the RF Front End

The challenge and complexity of 5G RFFE design is derived from the initial 3GPP standards for 5G calling for NSA (non-stand-alone) network which relies on 4G LTE as the anchor signal while 5G signals serve as a supplemental bandwidth added upon the base layer of LTE connectivity. Current LTE RFFEs – especially ones designed at Category 16/18/20 – has already experienced growth in complexity with technologies such as multiple carrier aggregation and 4x4 MIMO. Needless to say, by adding this dual-radio 5G architecture to the mix, the 5G requirements will push the RF front-end design into stratospheric levels of difficulty. SA or stand-alone versions of 5G simplifies the RFFE slightly with a single radio chain instead of the dual radio of NSA but the growing number of 5G frequency band [and bandwidth] support needed for future networks will inevitably drive up the design challenge for OEMs. Smartphone makers want to avoid "re-inventing the wheel" when a new design is started. By using a pre-configured RFFE and adding new 5G capabilities that can be optimized for the entire RF chain bring enormous benefits for the OEM. Traditional RFFE designs are largely performed outside the realm of component manufacturers. Samsung, by virtue of its market presence, has resident RF expertise as well as manufacturing scale. OEMs typically take it upon itself to design their own RFFEs. Once completed, the OEMs source custom or standard RF parts from component manufacturers such as Broadcom/Avago, Skyworks, Qorvo and Murata. But that model of RFFE design in the age of 5G is falling apart under the load of complexity. The preferred solution at the moment is to outsource that RF expertise. For Samsung, they have leaned heavily on Qualcomm's Modem-RF system for their flagship Galaxy S series.

While the 1st Gen 5G smartphone supported only single or dual band 5G, the 2nd Gen designs like the Samsung Galaxy S20 now support much more. The Galaxy S20 Ultra under review here is model number SM-G988U1 for the North American market which supports low band FDD 5G like n5 (850MHz) and n71 (600MHz) as well as mid-to-high bands like n2, n41 and n66. For 5G global roaming, the Galaxy S20 Ultra also included the common Ultra-High Frequency (UHF) 5G band n78. Further, the Galaxy S20 Ultra has millimeter wave (mmWave) antenna modules in addition to the Sub-6GHz RFFE. The new Qualcomm QTM0525 antenna modules in the Galaxy S20 Ultra support an additional four ultra-wide 5G bands (n258, n257, n260 and n261). So how do all these RF capabilities come together inside the Galaxy S20? Let's dive in for a closer look.

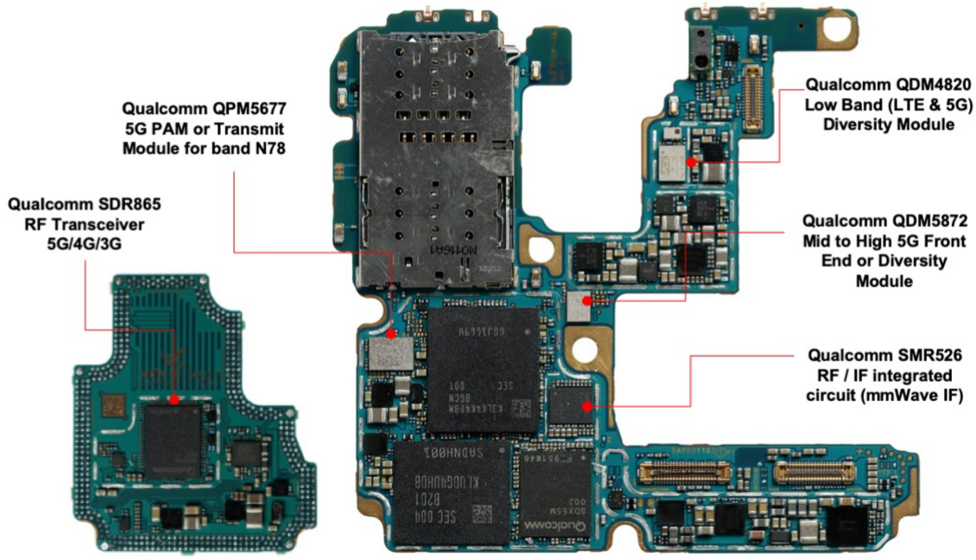

Figure 4: Samsung Galaxy S20 Ultra (top side PCB); major components identified in 5G RFFE

Qualcomm's 2nd Gen Snapdragon X55 Modem-RF system opens up more 5G frequency band support including the high coverage, low frequency FDD variety. Low band 5G helps carriers achieve network coverage but the bandwidth of these 5G bands are similar to that of LTE and therefore not significantly faster. The existing low-band PAMiD or transmit modules perform double-duty for both LTE and 5G radios in this case.

Downlink MIMO, Uplink MIMO and Antenna Tuning

In the Galaxy S20 Ultra, we find support for band n41 with the Qualcomm QPM6585 PAMiF or transmit module. As the network uplink channel moves into the mid-band and beyond, the handset begins to experience deviations of downlink and uplink coverage with the uplink shrinking relative to the uplink. To compensate for this, RF components have been increasing the output power of the device transmitter for mid-band signals. This industry standard of HPUE (high-power UE) components, specifically the mid-band PAMiFs, solves most of the issues in the mid-band uplink. HPUE technology from LTE carries over to 5G RFFEs.

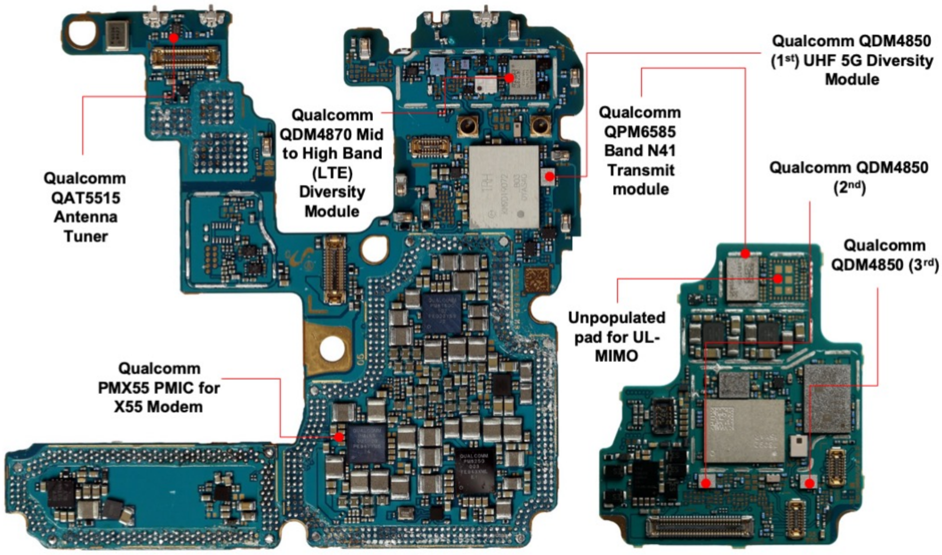

Figure 5: Samsung Galaxy S20 Ultra (bottom side PCB); major components ID in 5G RFFE

Another challenge is the requirement for 4x4 downlink MIMO dictated within the 5G standards. While LTE devices has started offering 4 spatial layers on mid to high LTE bands, the challenge of wider 5G bandwidths calls for additional RFFE capabilities. Within the Galaxy S20 Ultra, multiple Qualcomm QDM5872 diversity modules are used to support the downlink MIMO for band n41.

Moving on to the upper end of the Sub-6GHz 5G RFFE, the Galaxy S20 Ultra has an additional radio chain specific to band n78. Band n78 is a TDD 5G spectrum that is centered around 3.5GHz. By adding Band n78 support, Samsung is future-proofing the device for eventual 5G global roaming. Here, Qualcomm supplies radio components for the UHF band. The Qualcomm QPM5677 is the primary PAMiF for band n78 with 3 additional Qualcomm QDM4850s diversity modules to capture the additional 3 spatial streams to achieve 4x4 MIMO on this particular 5G frequency.

Uplink-MIMO improves on the uplink transmission in by leveraging the RF benefits of MIMO. At cell edge, the use of UL-MIMO is useful to keep the 5G uplink signal fidelity. The implementation of UL-MIMO would require an additional PAMiF for band n78 in the design. Within the Galaxy S20, we do see unpopulated pads on the PCB just for this design option. In other models, especially international 5G models, UL-MIMO on band n78 is becoming commonplace.

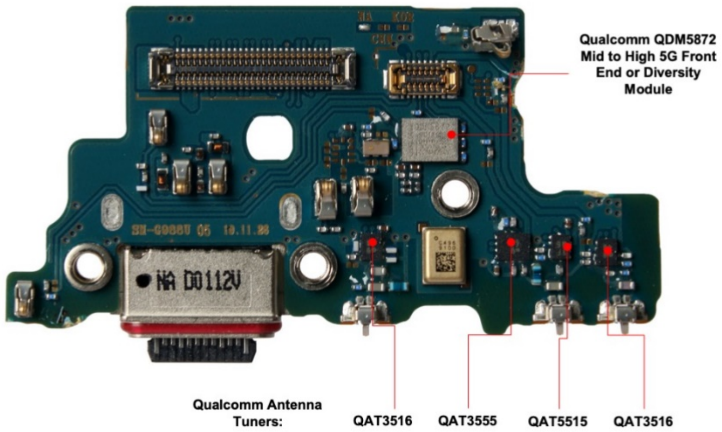

Figure 6: Samsung Galaxy S20 Ultra (interconnect PCB); 5G diversity module and 4 antenna tuners

With all these different higher 5G frequencies requiring 4x4 MIMO, antenna design becomes much more daunting in modern 5G devices. A typical LTE device may have upwards of 6 cellular antennas. Some high-end devices exhibit more due to the higher number of frequencies supported. However, the volume inside a device like the smartphone is still finite and designers can only fit in so many physically tuned antennas. The solution for that are antenna tuners. Antenna tuners are vital to 5G as higher frequencies and 4x4 MIMO requirements drive up need for more antennas. In the case of the Galaxy S20 Ultra design, Samsung is using up to five Qualcomm antenna tuners in the design.

mmWave 5G Antenna Modules Does Come Included

The first 5G devices in the US were based on mmWave technology. The 1st generation 5G devices were either using Qualcomm's mmWave antenna module design for mmWave networks (Verizon, AT&T, T-Mobile) or a more conventional RFFE design for sub-6 GHz 5G networks (Sprint). However, that represented a design compromise since each variant would be shut out from other 5G network. With the 2nd Gen 5G designs like the Galaxy S20 Ultra, OEMs are adding mmWave capabilities along with Sub-6 GHz 5G RFFE on the same device. This dual RFFE design allows flagship devices to be network agnostic, opening up many more 5G network and also benefits Samsung by reducing 5G SKUs.

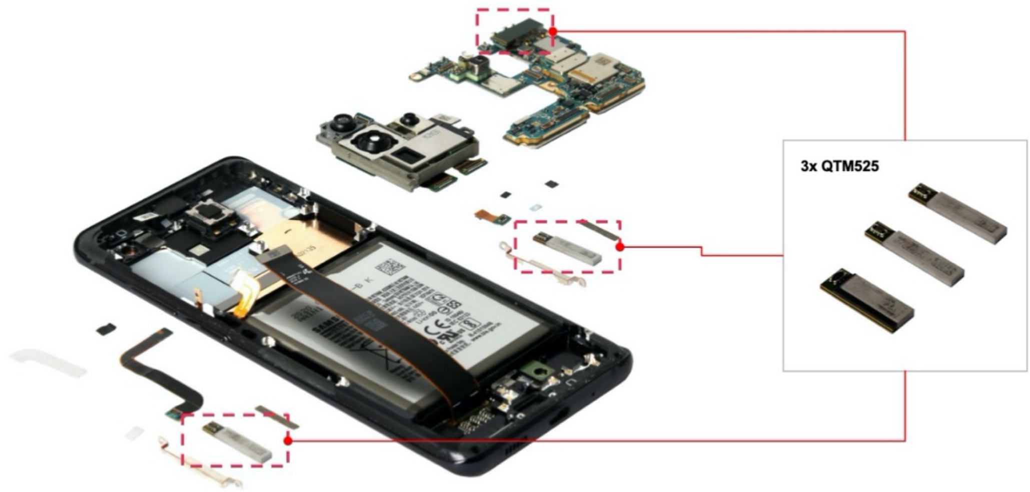

Figure 7: Samsung Galaxy S20 Ultra (disassembly view); mmWave 5G antenna modules from Qualcomm (QTM525)

For mmWave 5G for mobile, there is still only one supplier of commercially available solutions on the market today. Qualcomm's QTM052 was the choice of the 1st Gen 5G phones. For the latest generation of 5G mmWave devices, Qualcomm is offering an updated Qualcomm QTM525 antenna module. Taking feedback from OEM customers, Qualcomm decreased the width and profile of the antenna modules so to better fit within the narrow bezels or mid frames of the device. Also, new 24GHz support was added to the Qualcomm QTM525. However, unlike the Qualcomm QTM052, the intermediate frequency (IF) chip has been offloaded onto a single integrated circuit directly mounted on the top side of the main PCB. This is the Qualcomm SMR526 IF IC shown on figure 3.

For a full accounting of the Qualcomm Snapdragon X55 Modem-RF system used in the Galaxy S20 Ultra, the following table contains select bill of materials (BOM) items to illustrates the extent of the Qualcomm's design win.

Location	QTY	Part Number	Description
Main PCB	1	SM8250	Apps Processor, Qualcomm Snapdragon 865, Octa-Core 64-Bit Kryo 585 CPU, Single-Core 2.84GHz + Triple-Core 2.42GHz + Quad-Core 1.8GHz, Adreno 650 GPU, 7nm FinFET, PoP
Main PCB	1	SDX55M	Baseband Processor, Qualcomm Snapdragon X55, 5G Multi-Mode, Multi-Band, GSM/EDGE/WCDMA/TD-SCDMA/LTE/5G NR(mmWave / Sub-6GHz), FDD/TDD/SA/NSA, w/ Integrated SDRAM
Interface / RF PCB	1	SDR865	Qualcomm RF Transceiver, Multi-Mode, Multi-Band, GSM/EDGE/WCDMA/LTE/5G NR, GPS/GLONASS/BEIDOU
Main PCB	1	SMR526	Qualcomm RF / IF IC

Main PCB	1	QPM5677	Qualcomm Transmit Module, PAM, 5G NR n77/n78, Contains Qualcomm RF Switch & PA & LNA, w/ Bandpass Filter
Interface / RF PCB	1	QPM6585	Qualcomm Transmit Module, PAM, 5G NR n41, Contains Qualcomm RF Switch & PA & LNA, w/ BAW Filter
mmWave Antenna Module B	2	QTM525-501-BA	Qualcomm mmWave Antenna Module, Contains 2 Qualcomm RF ICs, 5G NR n257/n258/n260/n261, w/ Multilayer Package Substrate Antenna Array, 1 Board to Board Plug
mmWave Antenna Module A	1	QTM525-601-BA	Qualcomm mmWave Antenna Module, Contains 2 Qualcomm RF ICs, 5G NR n257/n258/n260/n261, w/ Multilayer Package Substrate Antenna Array, 1 Board to Board Plug
Main PCB	1	QDM4870	Qualcomm FEM, Mid & High Band, Contains Qualcomm RF Switch & LNA, w/ SAW Filters
Main PCB	1	QDM4850	Qualcomm FEM, Ultra-High Band, Contains Qualcomm LNA, w/ BAW Filter
Main PCB	1	QDM4820	Qualcomm FEM, Low Band, Contains Qualcomm RF Switch & LNA, w/ SAW Filters
Main PCB	1	QDM5872	Qualcomm FEM, 5G NR (Mid & High Band), Contains Qualcomm RF Switch & LNA, w/ SAW Filters
Interface PCB	1	QDM5872	Qualcomm FEM, 5G NR (Mid & High Band), Contains Qualcomm RF Switch & LNA, w/ SAW Filters
Interface / RF PCB	2	QDM4850	Qualcomm FEM, Ultra-High Band, Contains Qualcomm LNA, w/ BAW Filter
Main PCB	1	QET6100	Qualcomm Power Management IC, Envelope Tracking
Main PCB	1	QAT5515	Qualcomm Antenna Tuner
Interface PCB	2	QAT351x	Qualcomm Antenna Tuner
Interface PCB	1	QAT355x	Qualcomm Antenna Tuner
Interface PCB	1	QAT5515	Qualcomm Antenna Tuner
Main PCB	1	PM3003A	Qualcomm Power Management IC
Interface / RF PCB	2	QET5100	Qualcomm Power Management IC, Envelope Tracking
Main PCB	1	PM8150C	Qualcomm Power Management IC
Main PCB	1	PM8250	Qualcomm Power Management IC
Main PCB	1	PMX55	Qualcomm Power Management IC

Chart 1: Qualcomm content within Samsung Galaxy S20 Ultra (Bill of Materials)

Note: The Korea SKU of the Galaxy S20 Ultra consists of nearly identical components as in the table above with exception for the mmWave modules. (The regional 5G spectrum support will require modifications in PAMiF and diversity modules)

Challenges Ahead

The differences between the 1st generation and 2nd generation 5G designs are put on full display here in this whitepaper. 5G designs will continue to challenge OEMs with increasing number of frequency support, 5G carrier aggregation, antennae, uplink MIMO as well as co-existing mmWave/Sub-6 RFFEs. All of these growing 5G complexities presents a daunting engineering burden for device makers. By identifying these pain-points, the industry can begin to address the problems. For Qualcomm, they have demonstrated, through their 2nd Gen 5G design wins, their commitment to offer leading OEMs like Samsung an integrated 5G modem to RF system. For Samsung, choosing to use Qualcomm's solution [rather than their own] speaks to their need to arrest the growing 5G complexity as well as their trust in the Qualcomm Snapdragon Modem-RF system. By outsourcing the 5G complexity, handset OEM can continue to add more global 5G support without depleting their engineering resources while decreasing time-to-market. In the coming years of global 5G transition, smartphone OEMs will look for "pre-baked" 5G Modem-RF system to add to their 5G devices. Ambitious OEMs needing to expand into new global markets will be keen to pick up a proven 5G modem to antenna solution to address 5G networks outside of their domestic market. 5G is an ever-evolving wireless standard and by tackling RF complexity provides OEMs with a competitive edge in a hyper-competitive market.

An area that was not touched on was the role of envelope tracking (ET) in 5G. As the number of PAMiFs increases due to UL-MIMO, special attention has to be paid to the power consumption of the device. Envelope trackers have been very effective in LTE, however, 5G bandwidths can be much wider. In order to most efficiently transmit, the UE will require wide bandwidth ET solutions. Qualcomm currently offers the QET6100 which can handle up to 100MHz bandwidth in Sub-6 GHz RFFEs. But more progress is required to continue improving power efficiency in future 5G RFFE.

Conclusion

In order to realize the transformative benefits of 5G, the underlying wireless technology must be readily available. For Qualcomm, winning the 1st Gen 5G design was expected given its industry leadership in 5G modems. However, to continue winning future 5G designs – especially with the addition of the RF section – is not only significant from the business aspect but a technical one as well. This teardown analysis of the Samsung Galaxy S20 series highlights just that. 5G design is all about managing complexity. This means that the entire modem to antenna system must be taken into consideration to creating an optimized design. Qualcomm's offering of an integrated 5G Modem-RF system continues to gain strong traction with device manufacturers such as Samsung and likely many more leading global OEMs.

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