HETEROGENEOUS INTEGRATION ROADMAP

2019 Edition

Chapter 12: 5G Communications

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We acknowledge with gratitude the use of material and figures in this Roadmap that are excerpted from original sources.

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Chapter 12: 5G Communications

1.0 Executive Summary

The fifth generation mobile communications (5G) segment represents new opportunities for IC packaging technology that significantly different from previous generations of cellular-based mobile wireless technologies. This roadmap identifies challenges in 5-, 10-, and 15-year horizons and provides guidance on how to meet those challenges. This is, of course, a perpetual work-in-progress and will be updated as capabilities move forward and new requirements arise.

2.0 HIR 5G Technology Working Group

2.1 Mission Statement for 5G TWG

The mission of the Heterogeneous Integration Roadmap for 5G is to identify challenges, provide guidance, and recommend solutions for the next generation of RF Front-End (RFFE) electronics to inform industry, academia, and government with sufficient lead time that they do not become roadblocks preventing the continued implementation of leading-edge electronics in transformational connectivity systems.

There is the need to address heterogeneous integration technologies for new capabilities for RFFE, embedded high-speed computing, sensors, and signal processing, all while addressing unique constraints and requirements, such as size, weight, power and cost.

The approach is to identify the requirements for heterogeneous integration in the RFFE electronics industry with 5-, 10- and 15-year horizons, determine the difficult challenges that must be overcome to meet these requirements and, where possible, identify potential solutions and synergies with the other HIR commercial sectors.

2.2 The TWG for Developing the Heterogeneous Integration Roadmap for 5G Communications

The goal for the 5G Technology Working Group (TWG) is to develop a roadmap for heterogeneously integrated components for applications in the emergent 5G vertical and to leverage heterogeneous integration technologies that are becoming available in the advanced packaging industry. This 5G chapter will not repeat the heterogenous integration metrics for linewidth, pitch and materials substrates that are found in the other HIR chapters. Instead, reference to appropriate chapters will be made to provide cross-references.

Specific goals:

- Identify the 5G-specific challenges in the next 3, 5, and 10 year horizon
- Identify the future networks challenges for 6G (10 to 15 years)
- Identify promising solutions and technologies
- Identify any unaddressed challenges and the types of solutions/technologies needed
- Document all of these as a chapter in the overall HIR document
- Continue monitoring and analyzing the 5G semiconductor space to update the roadmap in the next version of this HIR

2.3 Cross HIR TWG Teams

The 5G HIR TWG addresses the applications of heterogeneous integration for the 5G application as a system vertical. Therefore, the 5G hardware needs for advanced packaging will rely on the underlying 2.5D/3D technologies and capabilities for Interconnects, WLP, Thermal Management, Test, SiP and Module, Single Chip & Multi-Chip Integration, Co-Design, Security, MEMS and Sensors, and Supply Chain. The adjacent chapters for products such as Mobile, Aerospace and Defense, Medical, IoT and Automotive will also be important for cross-team communications since they have similarities in needs or can be adopted as good starting points for 5G systems. For example, once V2X (Automotive) becomes a driver, then the 5G radios that go inside automobiles will need to be packaged to the same environmental conditions as for automotive electronics. As more highly-integrated RFICs become available, it may change the balance in the trade-off study between antenna-in-package and antenna-on-chip strategies. Of course, Mobile will cover both conventional 4G and sub-6GHz RF Front-ends.

3.0 Introduction and Motivation

Without unnecessarily repeating the history of cellular mobile communications, this chapter will focus on 5G-related technology challenges. We refer you to view historical summaries available elsewhere.[1], [2] Up-to-date annual reports on the 5G ecosystem are provided by GSMA in their Mobile Economy 2019 Report[3] and the Ericsson Mobility Report 2019.[4]

3.1 Comparison with Current State-of-the-Art: Differences Between 4G and 5G

Compared to 4G and 4G LTE, 5G is not evolutionary but revolutionary in the number and kind of use cases that cannot be supported in the prior cellular generations. Figures 3-1 and 3-2 compare the two generations for latency, peak data rates, and connection density. Technology needs for 5G devices can be examined with specific needs at the two frequency domains: below 6 GHz, and millimeter-waves. In the subsequent sections in this document, packaging technologies that are appropriate to address the differences in 5G architectures, and performance metrics (data rates, latency, capacity), will be highlighted.

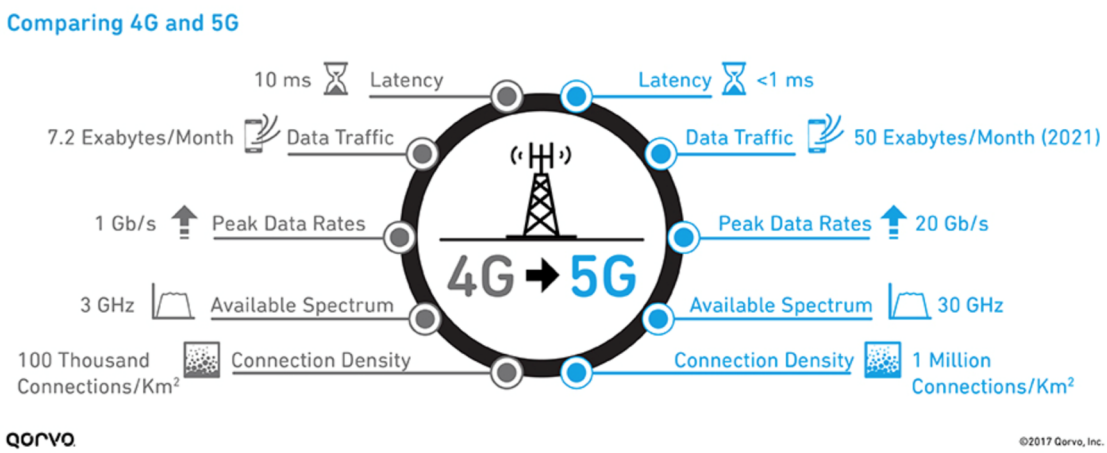


Figure 3-1. Comparing 4G and 5G[5]

	4G (Today, Before Further Developments)	5G
Latency	10 ms	Less than 1 ms
Peak data rates	1 Gbps	20 Gbps
Number of mobile connections	8 billion (2016)	11 billion (2021)
Channel bandwidth	20MHz 200kHz (for Cat-NB1 IoT)	100MHz below 6GHz 400MHz above 6GHz
Frequency band	600MHz to 5.925 GHz	600MHz–mmWave (for example, 28GHz, 39GHz, and onward to 80 GHz
Uplink waveform	Single-carrier frequency division multiple access (SC-FDMA)	Option for cyclic prefix orthogonal frequency-division multiplexing (CP-OFDM)
User Equipment (UE) transmitted power	+23 decibel-milliwatts (dBm) except 2.5GHz time- division duplexing (TDD) Band 41 where +26dBm, HPUE is allowed IoT has a lower power-class option at +20dBm	+26dBm for less than 6GHz 5G bands at and above 2.5GHz

Figure 3-2. Key Performance Metrics Comparison Between 4G and 5G (Qorvo)[3]

[1] "List of mobile phone generations," found at https://en.wikipedia.org/wiki/List_of_mobile_phone_generations
[2] "A Brief History of Mobile Communications," found at http://www.winlab.rutgers.edu/~narayan/Course/Wireless_Revolution/vts%20article.pdf
[3] https://www.gsmaintelligence.com/research/?file=b9a6e6202ee1d5f787cfebb95d3639c5&download
[4] https://www.ericsson.com/en/mobility-report?gclid=Cj0KCQjw5MLrBRClARIsAPG0WGw5xklTaaiwfiMXQr8WtcGyqxeqWUnvxrLuZFX9TT7IC2zaZhQgN64aAnO7EALw_wcB
[5] https://www.qorvo.com/design-hub/blog/getting-to-5g-comparing-4g-and-5g-system-requirements

3.2 5G Architecture

As envisioned by 3GPP Release 15, the 5G architecture will address three differentiated use cases (Figures 3-3 and 3-4):

- Enhanced Mobile Broadband – eMBB
- Ultra Reliable Low Latency Communications – URLLC
- Massive Machine to Machine (Internet of Things) – MM2M

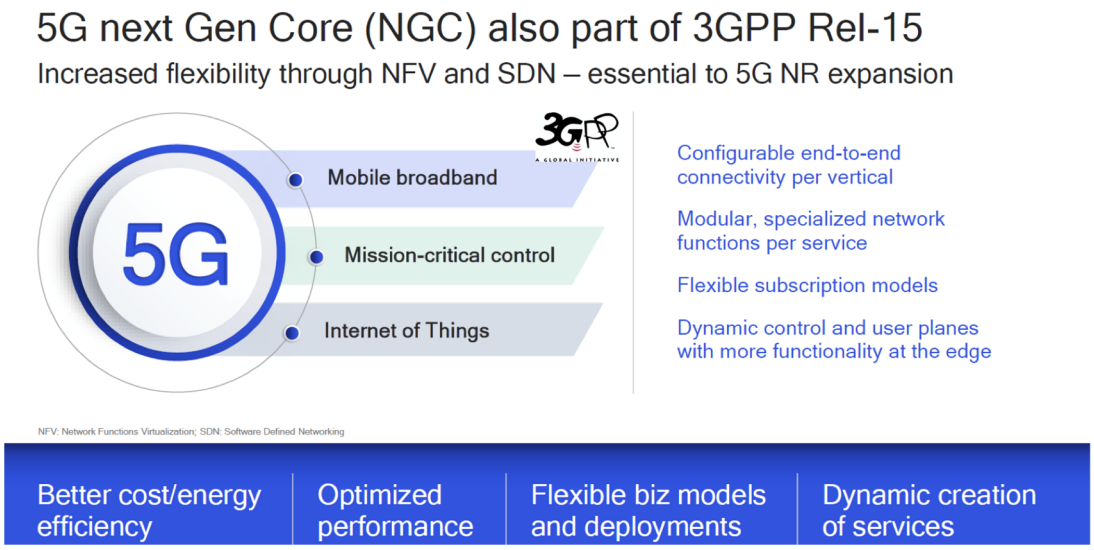


Figure 3-3. 5G Next Generation Core Use Cases[6]

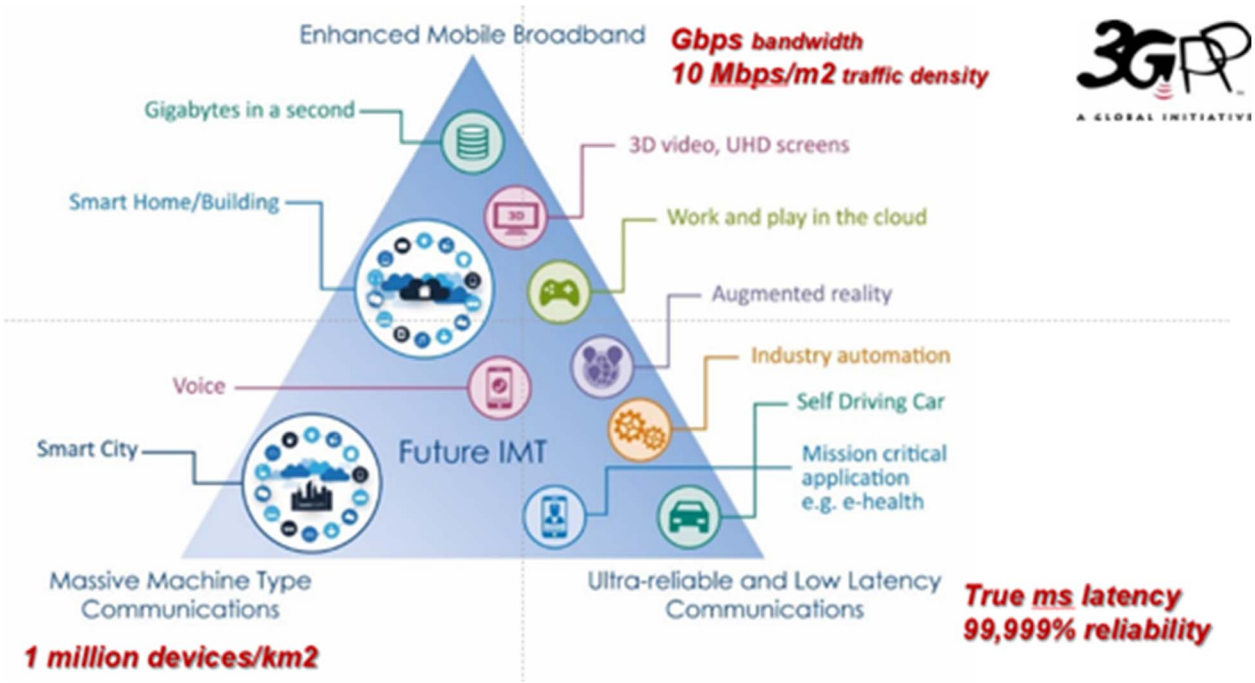


Figure 3-4. 3GPP Architecture for 5G Use Cases

[6] Qualcomm: "Making 5G NR a Commercial Reality A unified, more capable 5G air interface," found at https://www.qualcomm.com/media/documents/files/making-5g-nr-a-commercial-reality.pdf

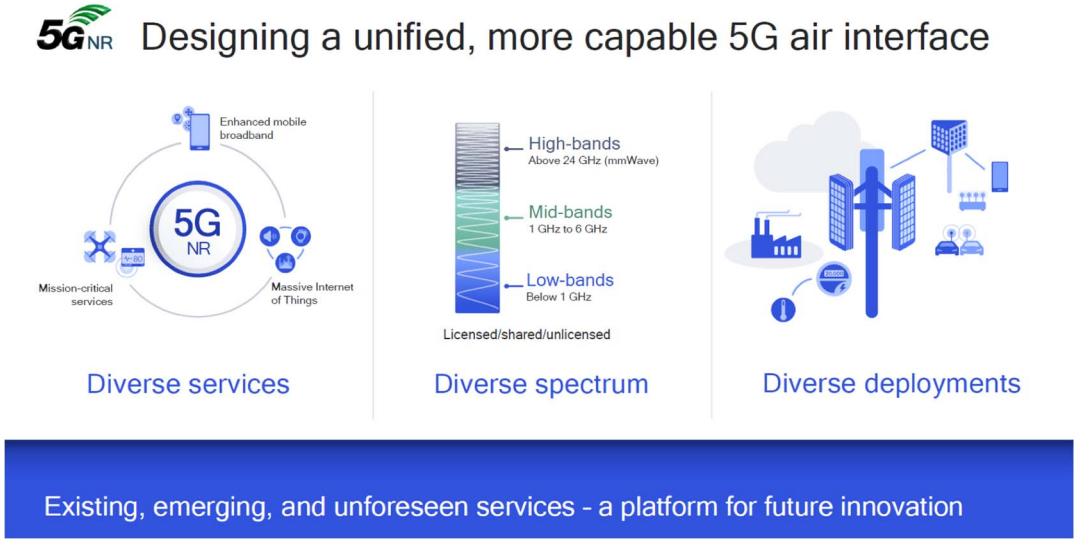


Figure 3-5. 5G Ecosystem Offers Diverse Services, Spectrum and Deployments[7]

3.3 5G Use Cases

Figure 3-6 shows a spider chart comparing the key metrics for 4G and 5G. 5G will out-perform its predecessors in almost all metrics. Figure 3-7 and 3-8 show examples of two 5G use cases: Fixed Wireless, and Mobility.[8] 5G Fixed Wireless deployments have already begun in 2019 and represent the simpler air interface that enables an alternative to other fixed broadband services (cable, fiber and DSL). The Mobility Use Case for 5G introduces the need for small cells since millimeter-wave signals do not propagate very far. This limitation will drive specific solutions for active, passive and radiators used for the 5G RF Front-Ends (RFFE) for which advanced packaging will play an increasingly important role. The Vehicle-to-X (V2X) application represent an example of the URLLC use case (Figure 3-9). Even for this application, there will be tradeoffs for Latency, Data Rate, Reliability and Range (Figure 3-10).

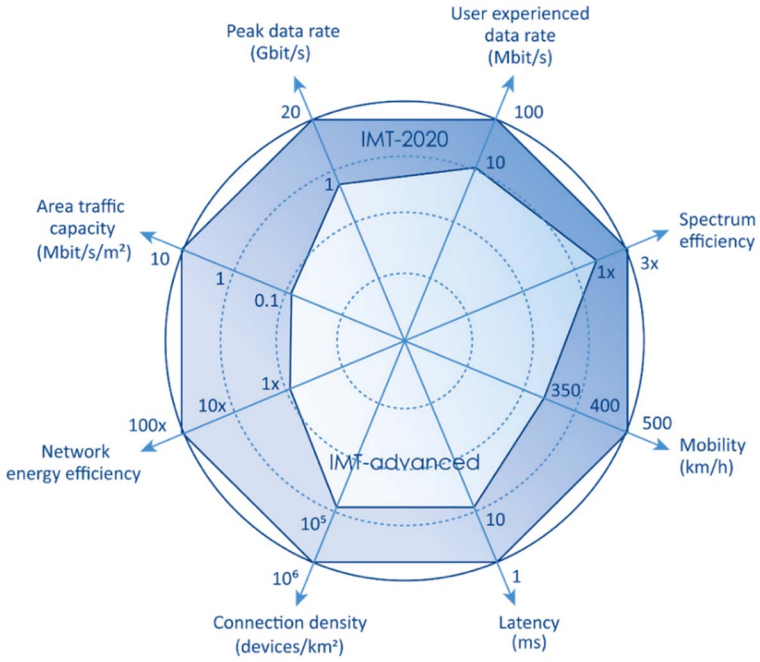


Figure 3-6. IMT Spider Chart Comparing IMT-Advanced (4G LTE) and 5G Capabilities[9]

[7] Qualcomm: "Making 5G NR a Commercial Reality A unified, more capable 5G air interface," found at https://www.qualcomm.com/media/documents/files/making-5g-nr-a-commercial-reality.pdf

8 https://www.globalfoundries.com/resources/technical-webinar-series/design-innovations-5g-mmwave-fems-and-phased-arrays

[9] https://www.etsi.org/technologies/mobile/5g

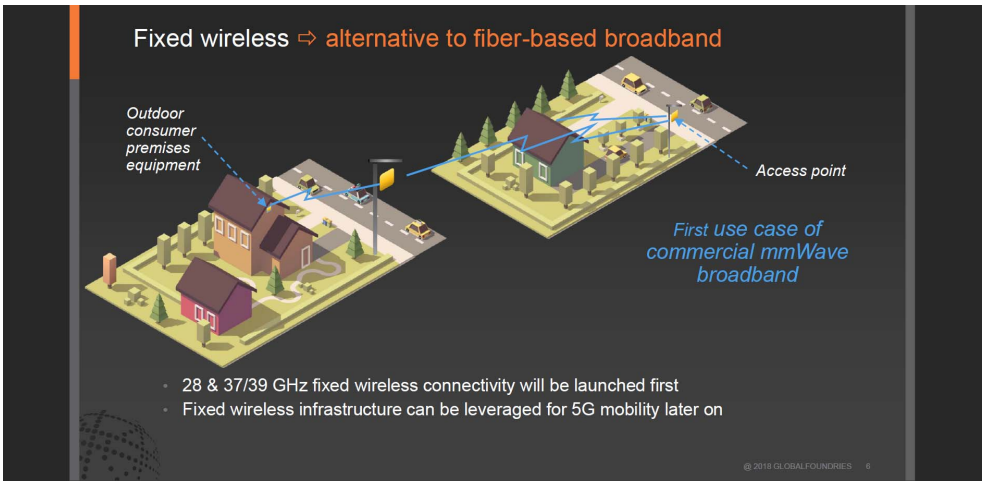


Figure 3-7. 5G Fixed Wireless Use Case (GlobalFoundries[6])

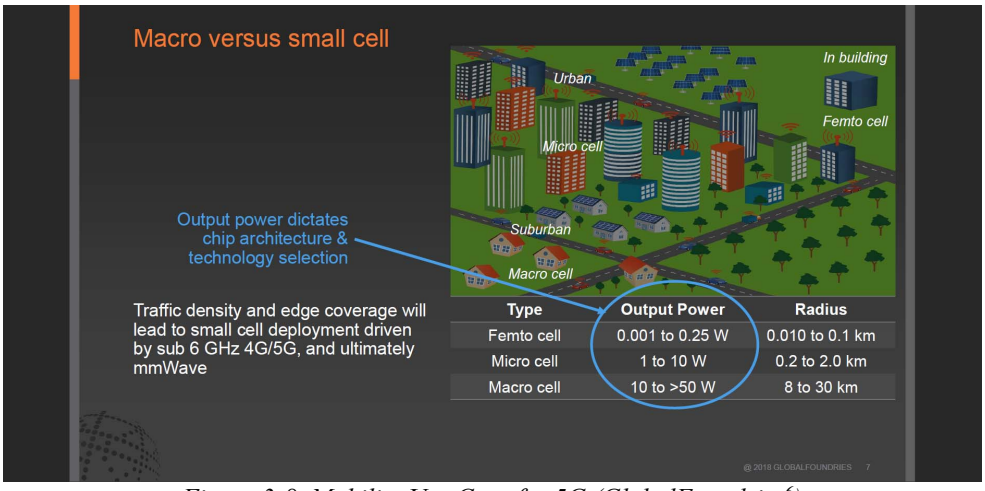


Figure 3-8. Mobility Use Case for 5G (GlobalFoundries[6])

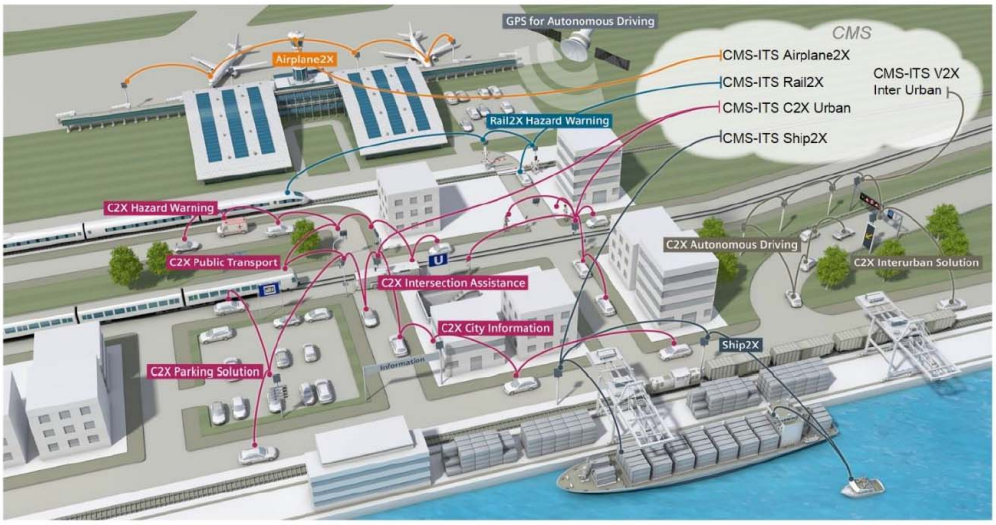


Figure 3-9. Example of 5G Use Case Supporting C2X[10]

[10] White Paper, "Ready to roll: Why 802.11p beats LTE and 5G for V2x," NXP & Siemens, found at https://assets.new.siemens.com/siemens/assets/public.1510309207.ab5935c545ee430a94910921b8ec75f3c17bab6c.its-g5-ready-to-roll-en.pdf

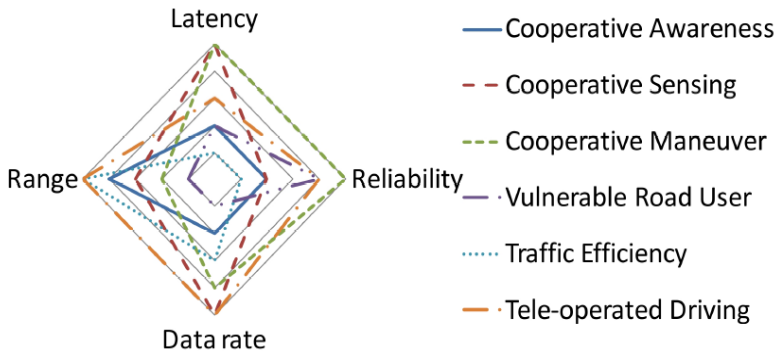


Figure 3-10. Different Communication Links for C2X have different Performance Requirements

3.4 5G Frequency Bands

As we discuss the availability of components, it is important to understand what frequency bands the devices will operate in. Figure 3-11 shows the frequency allocations in the US. It has been a challenge to find and allocate new spectrum that serves all users across national boundaries. Because of the availability of continuous bands below 6GHz, 4G LTE and below-6 GHz 5G use Carrier Aggregation (CA) techniques to improve data rates, while in the millimeter-bands, wider instantaneous bandwidth provides a better platform for extreme high data-rate communications. In Table 3-1 and Table 3-2 below, the 5G bands for millimeter-waves are listed. In the 3G era, a "world phone" had only four bands. Now 4G LTE phones need to support more than 40 bands. A 5G world phone will likely add another 6 to 10 bands. **Therefore, with the increased complexity, 5G phones will need much higher levels of component integration. This is the key motivation for the role of heterogenous integration.** 3GPP categorizes two Frequency Range Designations:

- FR1 450 MHz – 6000 MHz
- FR2 24250 MHz – 52600 MHz

More detailed explanations of 5G bands can be found at the ETSI website[11] (ETSI TS 138 104 V15.2.0 (2018-07).

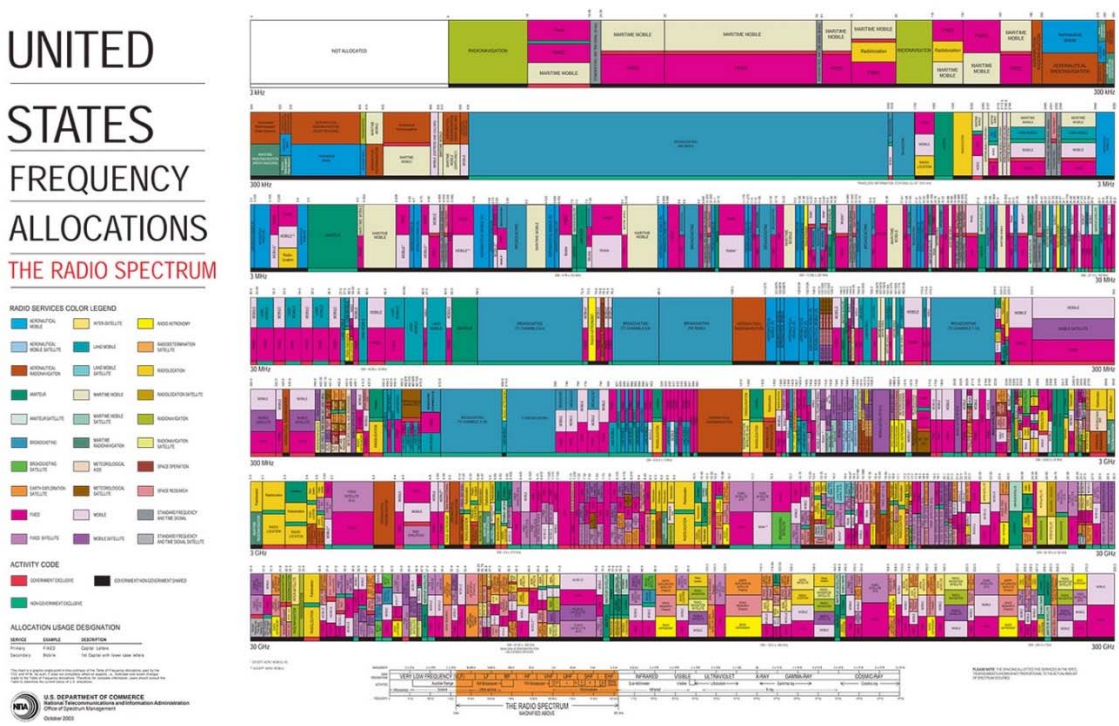


Figure 3-11. United States Frequency Allocations

[11] ETSI TS 138 104 V15.2.0 (2018-07) found at ETSI website, https://www.etsi.org/deliver/etsi_ts/138100_138199/138104/15.02.00_60/ts_138104v150200p.pdf

Table 3-1. NR Operating Bands in FR1 (450 MHz – 6000 MHz)

NR FR1 Band	***Band Alias***	***Uplink (UL) Operating Band BS Receive / UE Transmit F_{UL_low} – F_{UL_high}***	***Downlink (DL) Operating Band BS Transmit / UE Receive F_{DL_low} – F_{DL_high}***	***Bandwidth***	***Duplex Mode***
n1	2100	1920 MHz – 1980 MHz	2110 MHz – 2170 MHz	60 MHz	FDD
n2	1900 PCS	1850 MHz – 1910 MHz	1930 MHz – 1990 MHz	60 MHz	FDD
n3	1800	1710 MHz – 1785 MHz	1805 MHz – 1880 MHz	75 MHz	FDD
n5	850	824 MHz – 849 MHz	869 MHz – 894 MHz	25 MHz	FDD
n7	2600	2500 MHz – 2570 MHz	2620 MHz – 2690 MHz	70 MHz	FDD
n8	900	880 MHz – 915 MHz	925 MHz – 960 MHz	35 MHz	FDD
n20	800	832 MHz – 862 MHz	791 MHz – 821 MHz	30 MHz	FDD
n28	700 APT	703 MHz – 748 MHz	758 MHz – 803 MHz	45 MHz	FDD
n38	TD 2600	2570 MHz – 2620 MHz	2570 MHz – 2620 MHz	50 MHz	TDD
n41	TD 2500	2496 MHz – 2690 MHz	2496 MHz – 2690 MHz	194 MHz	TDD
n50	TD 1500+	1432 MHz – 1517 MHz	1432 MHz – 1517 MHz	85 MHz	TDD
n51	TD 1500-	1427 MHz – 1432 MHz	1427 MHz – 1432 MHz	5 MHz	TDD
n66	AWS-3	1710 MHz – 1780 MHz	2110 MHz – 2200 MHz	70/90 MHz	FDD
n70	AWS-4	1695 MHz – 1710 MHz	1995 MHz – 2020 MHz	15/25 MHz	FDD
n71	600	663 MHz – 698 MHz	617 MHz – 652 MHz	35 MHz	FDD
n74	L-Band	1427 MHz – 1470 MHz	1475 MHz – 1518 MHz	43 MHz	FDD
n75	DL 1500+	N/A	1432 MHz – 1517 MHz	85 MHz	SDL
n76	DL 1500-	N/A	1427 MHz – 1432 MHz	5 MHz	SDL
n77	TD 3700	3300 MHz – 4200 MHz	3300 MHz – 4200 MHz	900 MHz	TDD
n78	TD 3500	3300 MHz – 3800 MHz	3300 MHz – 3800 MHz	500 MHz	TDD
n79	TD 4500	4400 MHz – 5000 MHz	4400 MHz – 5000 MHz	600 MHz	TDD
n80	UL 1800	1710 MHz – 1785 MHz	N/A	75 MHz	SUL
n81	UL 900	880 MHz – 915 MHz	N/A	35 MHz	SUL
n82	UL 800	832 MHz – 862 MHz	N/A	30 MHz	SUL
n83	UL 700	703 MHz – 748 MHz	N/A	45 MHz	SUL

n84	UL 2100	1920 MHz – 1980 MHz	N/A	60 MHz	SUL

Table 3-2. NR Operating Bands in FR2

NR FR2 Band	***Band Alias***	***Uplink (UL) Operating Band BS Receive / UE Transmit*** F_{UL_low} – F_{UL_high}	***Downlink (DL) Operating Band BS Transmit / UE Receive*** F_{DL_low} – F_{DL_high}	***Bandwidth***	***Duplex Mode***
n257	28 GHz	26500 MHz – 29500 MHz	26500 MHz – 29500 MHz	3000 MHz	TDD
n258	26 GHz	24250 MHz – 27500 MHz	24250 MHz – 27500 MHz	3250 MHz	TDD
n260	39 GHz	37000 MHz – 40000 MHz	37000 MHz – 40000 MHz	3000 MHz	TDD

Figure 3-12 shows the 5G spectrum allocation differences between different countries. Without "harmonization" or consolidation of frequency bands, these multiple bands to support global operations will add to the design challenges for equipment makers for 5G UE and base-stations.

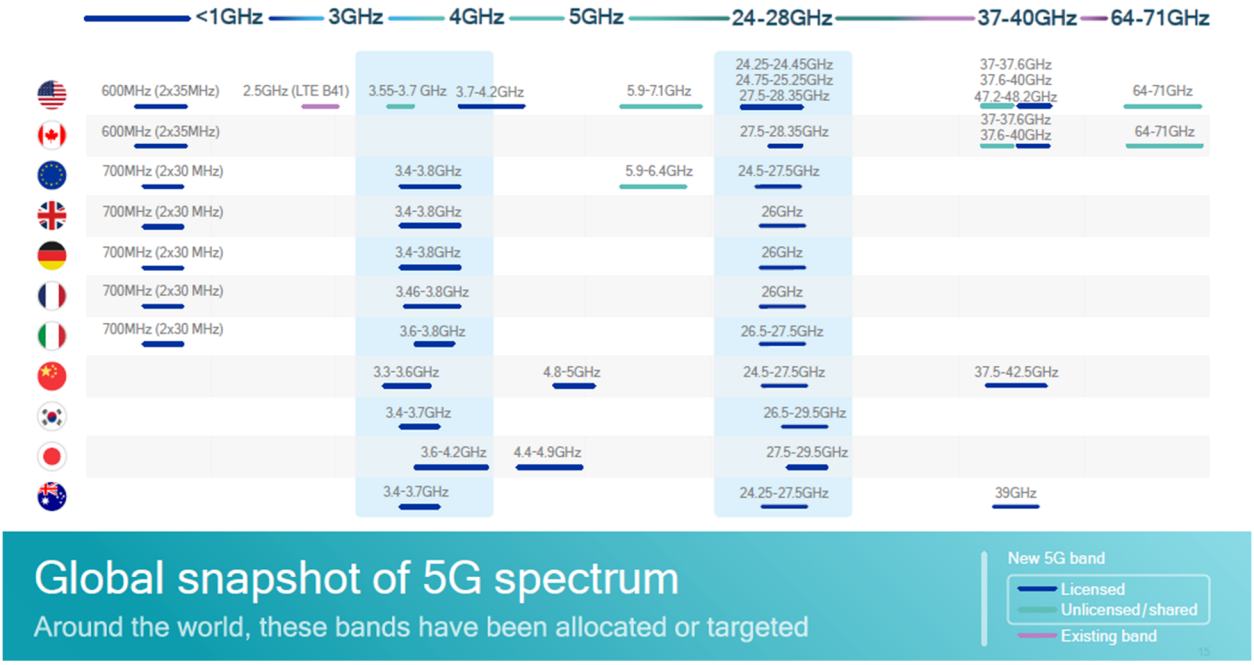


Figure 3-12. 5G Spectrum Across National Borders

2020 represents a critical milestone for 5G with the commercial launch of Rel-15 equipment and services (Figure 3-13) with the objectives of meeting the use case requirements shown in Figure 3-14.

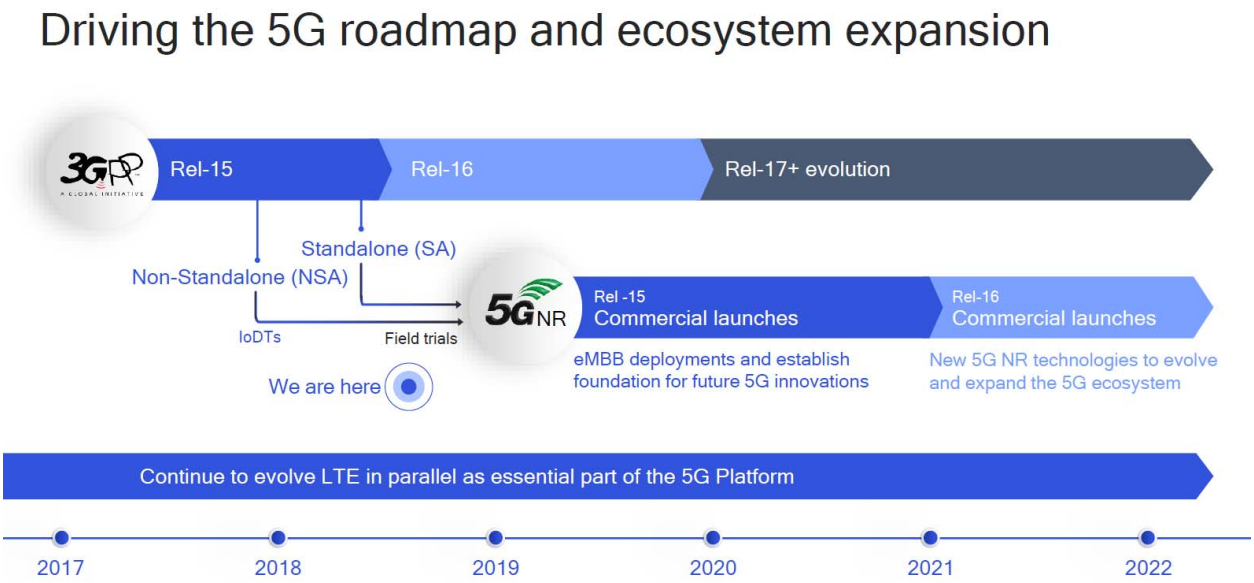


Figure 3-13. 5G Roadmap and Timeline (Qualcomm[12])

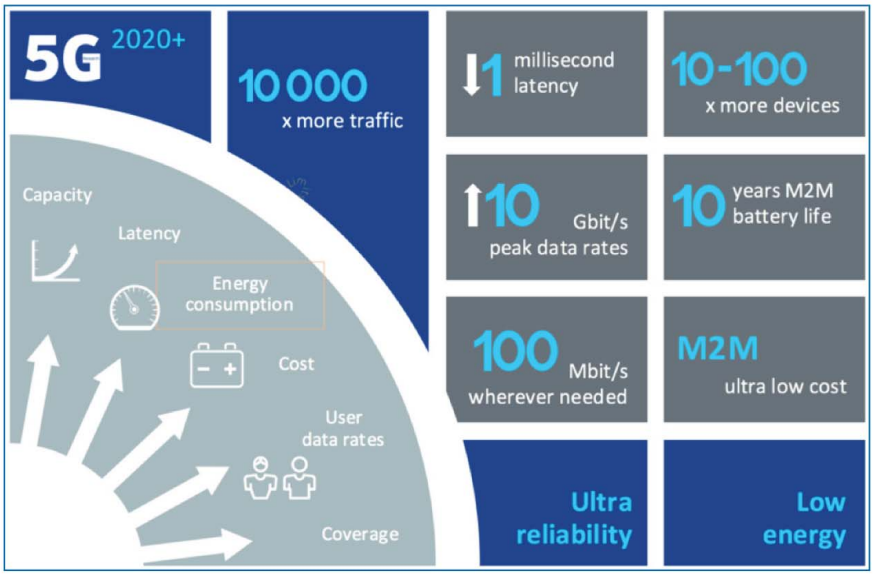


Figure 3-14 5G Use Cases (Nokia whitepaper[13])

4.0 Architectures for 5G RF Front-Ends

As was described in Section 3.2, there are new requirements for mid-band (2-6 GHz) and high band (n257, n258 and n260). Each set of requirements will require a different architecture for the 5G RF Front-End (RFFE), which is dependent on whether the equipment is at the base-station or at the User Equipment (UE).

The primary focus of this chapter is for millimeter-wave 5G bands and not addressing the requirements for mid- and low-bands. The prioritization also depends on the geographical location and for which carriers, as shown in Table 4-1. A 5G world phone will need to have 4G LTE, plus 5G low-, mid- and high-bands.

[12] Qualcomm: "Making 5G NR a Commercial Reality A unified, more capable 5G air interface," found at https://www.qualcomm.com/media/documents/files/making-5g-nr-a-commercial-reality.pdf

[13] https://technical.ly/brooklyn/2015/04/10/wireless-industry-5g-goals/

Table 4-1. 5G Bands by Geography and Carriers[14]

Bands	**n41 2.5 GHz**	**n78 3.5 GHz**	**n260 39 GHz**	**n261 28 GHz (US)**
Verizon Wireless	-	-	-	Yes
AT&T	-	-	Yes	-
Sprint	Yes	-	-	-
T-Mobile	-	-	-	Yes
Europe	-	Yes	-	-
China	Yes	Yes	-	-
India	-	Auctions end in 2019	-	-

To achieve millimeter-wave high-bandwidth connectivity, 5G systems will utilize beamforming technologies. Instead of wide-angle radiation patterns, narrow-focused beams will be used to track the UE devices as they move around within the operating radius of the cell site. Previously, this kind of phased-array technology (Figure 4-1) has been used in radar systems for tracking targets. Now with 5G, phased-array beamformers will be used at higher powers at the base-station and at lower power levels at the UE. Figure 4-2 describes three variants of beamforming: analog, digital and hybrid. Analog beamforming uses analog techniques to alter the amplitude and phase of the signal leaving each radiating element. Analog beamforming is simpler and more power-efficient as compared to digital beamforming. Digital beamforming is able to support multiple simultaneous beams but requires more power consumption due to analog-to-digital conversion needed at each element. The hybrid architecture is well suited for large arrays and has perhaps the optimum architecture for massive MIMO (256 elements or more).

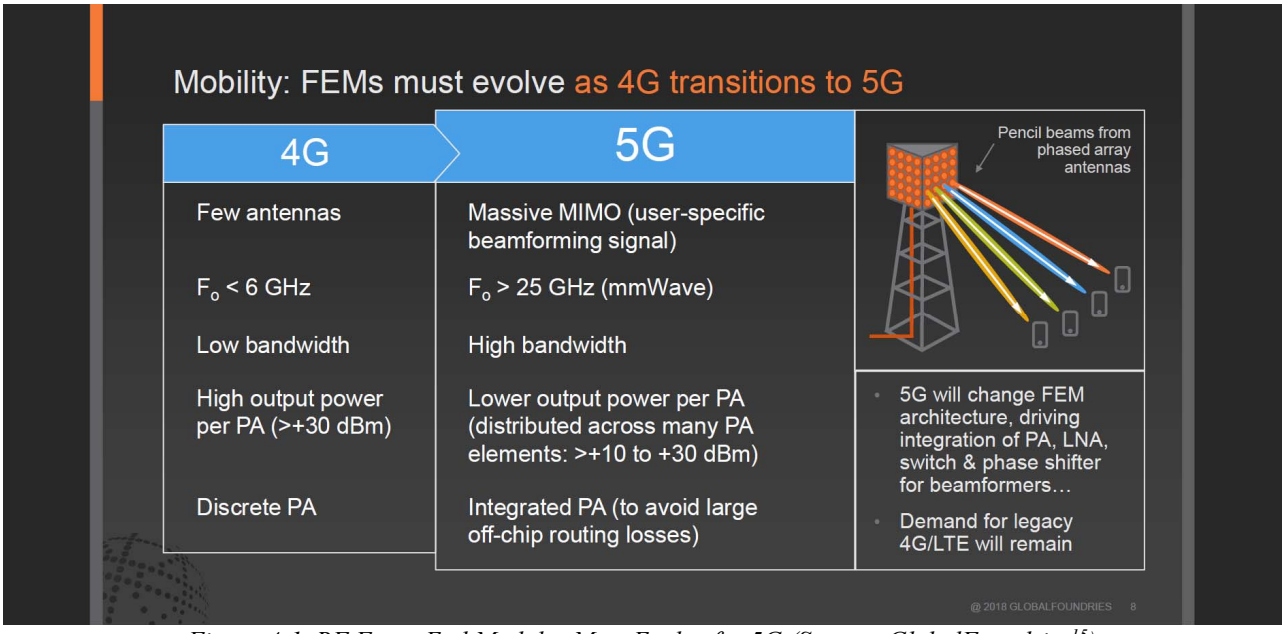


Figure 4-1. RF Front-End Modules Must Evolve for 5G (Source: GlobalFoundries[15])

[14] https://www.phonearena.com/news/5G-bands-explained-Verizon-vs-AT-T-vs-Sprint-vs-T-Mobile-vs-World_id116781
[15] https://www.globalfoundries.com/resources/technical-webinar-series/design-innovations-5g-mmwave-fems-and-phased-arrays

From architectural perspectives, the technical challenges for millimeter-wave 5G can be summarized into 3 challenges:

- **Challenge 1:** small element-to-element spacing needed for the phased-array (Figure 4-3)
- **Challenge 2:** appropriate semiconductor technology based on output power (Figure 4-4)
- **Challenge 3:** FEM integration level and packaging (Figure 4-6)

At 28 GHz, the maximum element-to-element spacing (Figure 4-3) is 5 mm. If the spacing is larger than the half wavelength (lambda/2), one ends up with undesired grating lobes in the antenna pattern. Because of this requirement, the use of heterogeneous integration – allowing tight integration of the actives (LNA & PA), filters and radiating element – is a key enabler for 5G RF Front-End Modules (FEM). There is no longer space available to assemble discrete components onto a PCB and attach a separate antenna. At 39 GHz, even further integration and size reduction will be required. In Section 5.4, we explore the benefits of Antenna in Package (AiP) versus Antenna on Chip (AoC) approaches.

The generation of millimeter-wave signals is more challenging than at 2 GHz. Therefore, a new technology for active semiconductor devices is needed to achieve the required gain, output power, linearity and noise figure to achieve a high-fidelity communication link. Figure 4-4 summarizes this challenge. Depending on deployment location, the transmit requirements for output power, power-added efficiency and number of phased-array elements vary significantly. In the UE case, the main constraints include battery life, antenna diversity and safe radiation levels due to proximity to the user's body. Therefore, the maximum power is about 200 mW (23 dBm), ~ 20% PAE and 0.6W DC power. Silicon Germanium (SiGe) and CMOS devices are appropriate to achieve the required transmit performance at millimeter-waves. For the small-cell base there may be 32 elements, and at the macro base-station there may be 256 elements.

Total Effective Isotropic Radiated Power (EIRP) across the different deployments can be achieved through two factors: number of elements X power per element. Therefore, the tradeoff must be made between available space at the platform that will limit the number of elements, versus the output power per element based on the semiconductor technology. At the larger base-stations, there is availability of more mains power to support higher-power transmitters based on Gallium Nitride (GaN).

The third challenge – the need for higher integration of added radio bands for 5G – is the biggest opportunity for the advanced packaging community represented by HIR to contribute to the success of the 5G ecosystem. Therefore, the research and development of 2.1D, 2.5D and wafer-level fanout techniques should be increased with emphasis on co-design and simulation of electrical, thermal, mechanical and reliability of the assembled product to deliver a manufacturable and high-yield outcome.

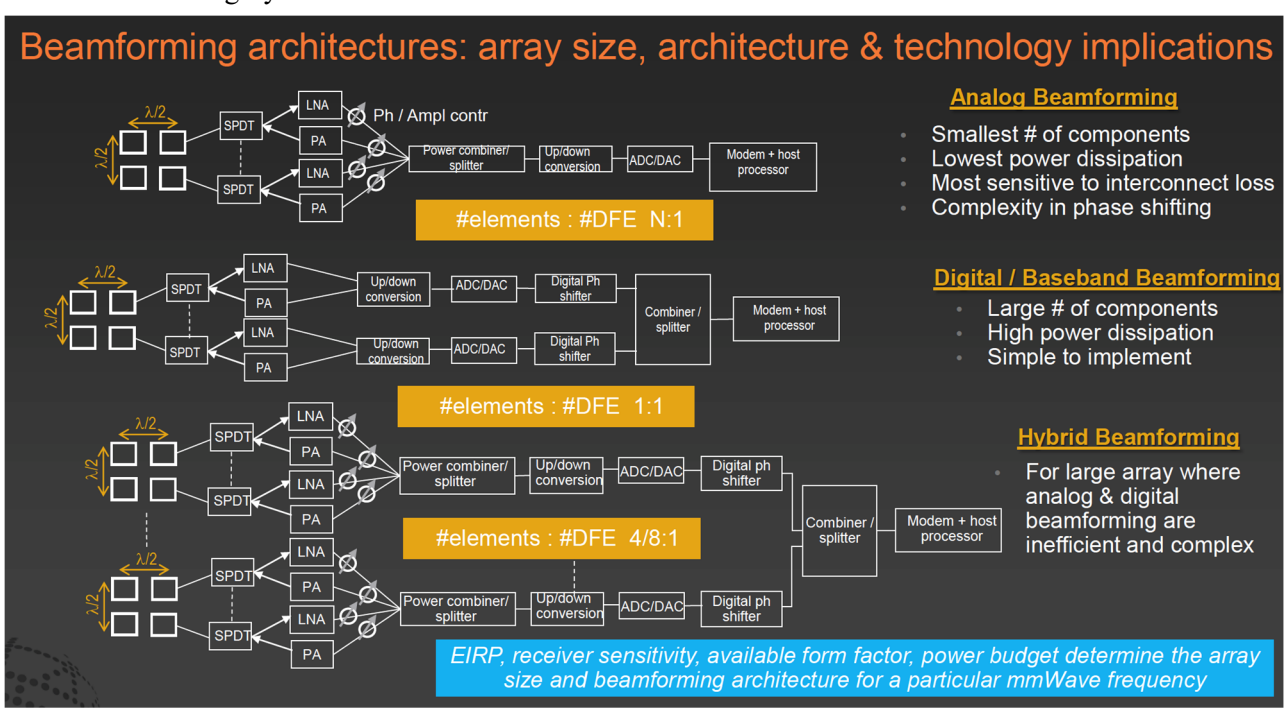
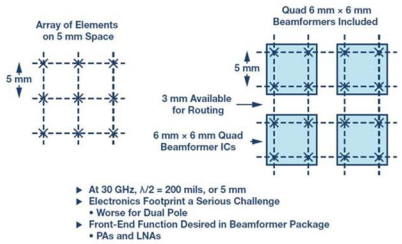


Figure 4-2. Comparison Between Analog, Digital and Hybrid Beamforming (GlobalFoundries[11])

Challenge 1: Tight Integration is Needed for mm-wave Phased Arrays



Frequency	Element Spacing	Dual Pole I/O Spacing
3 GHz	50 mm, 2 inches	25 mm, 1 inch
10 GHz	15 mm, 600 mils	7.5 mm, 300 mils
30 GHz	5 mm, 200 mils	2.5 mm, 100 mils

5G Front-End architecture (number of elements, EIRP, Si vs III-V, and Packaging) need to be tailored for each use case

Figure 4-3 Challenge of Tight Integration for mm-wave Phase Arrays[16]

Challenge 2: Selection of Semiconductor Technology Based on Output Level

5G Application Scenarios & Requirements 2018 (estimated)

	Handset	Access point	Base station	Backhaul	Last mile
EIRP (ave)	30 dBm	43dBm	60dBm	60dBm	75 dBm
Number antennas	4-6	32	256	256	256
Pave / PA	14dBm	11dBm	10dBm	10dBm	25dBm
Pmax/PA	23dBm	20dBm	19dBm	19dBm	33dBm
Efficiency (ave)	20%	20%	20%	20%	20%
DC power	0.6W	2W	12W	12W	390W

Estimated Power Ranges for 5G TX ICs & *Estimated* Max Power of Different Technologies

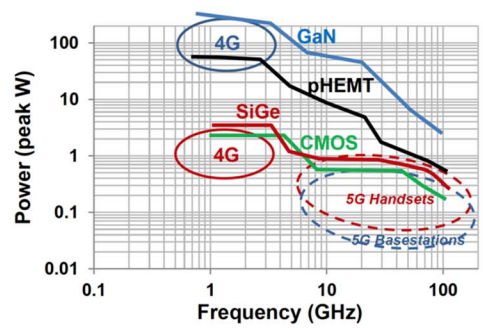


Figure 4-4. Challenge of Appropriate Semiconductor Technology for Required Output Power (Asbeck, UCSB)

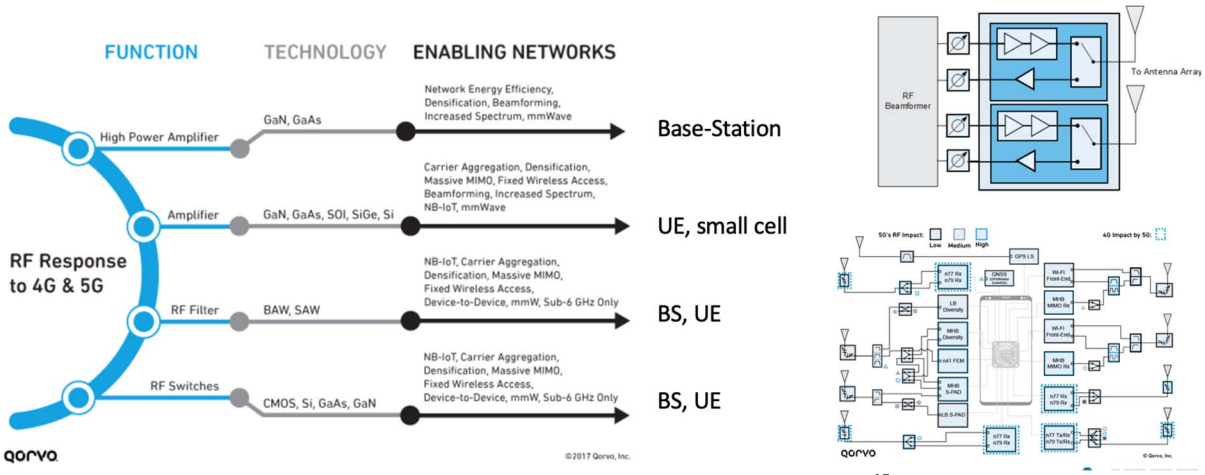


Figure 4-5. Semiconductor Technologies for 5G (Qorvo)[17]

[16] https://www.analog.com/en/technical-articles/a38400-physical-size-allocations-for-rf-electronics-in-digital-beamforming-phased-arrays.html

[17] https://www.qorvo.com/innovation/5g

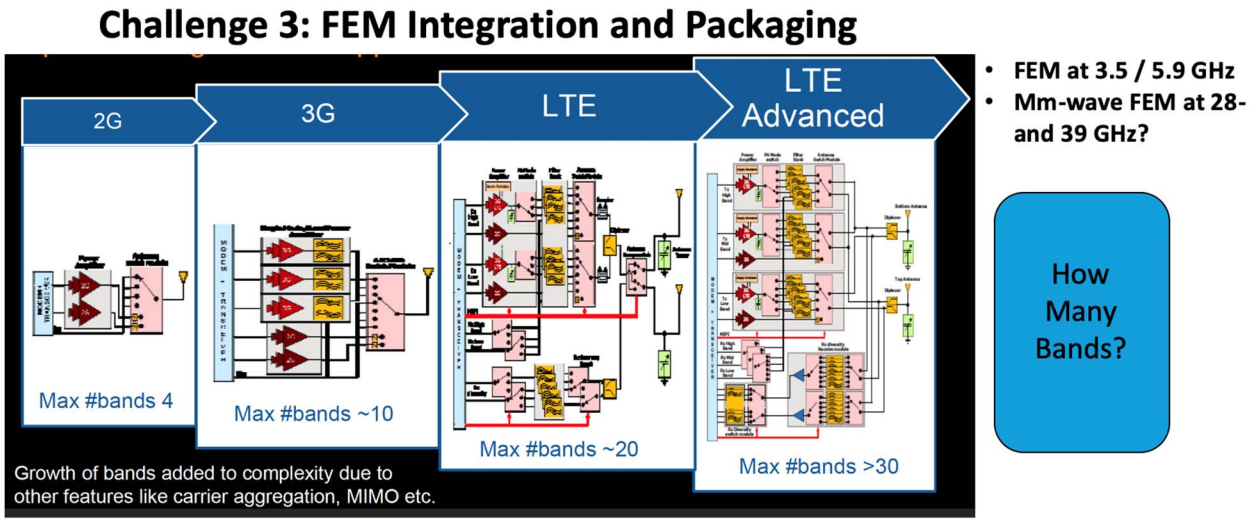


Figure 4-6. Increasing Complexity (Number of Bands) From 4G to 5G Will Drive Further FEM Integration and Packaging Challenges[18]

5.0 Heterogeneous Integration for 5G

In the context of this document, heterogeneous integration for 5G refers to all associated technologies, design techniques, simulation tools, materials and processes that are required to realize 5G RFFE at both below 6 GHz and at millimeter-waves. Section 5.1 addresses system drivers, Section 5.2 is on Inter-disciplinary challenges, Section 5.3 addresses current and future developments for Advanced SiPs for 5G. Section 5.4 specifically focuses on the tradeoffs for Antenna in Package (AiP) and Antenna on Chip (AoP). Section 5.5 shows examples of highly integrated 5G phased-arrays that leverage advanced packaging techniques. Finally, Section 5.6 shows the tear-down of the first 5G UE handset from Samsung. As more UEs are deployed, this section can be updated to show what advanced packaging techniques play a role.

5.1 What are system drivers?

System Drivers for 5G millimeter-waves in particular are listed below.

For >6 GHz bands (millimeter-waves)

- Materials (substrates, metal and dielectric losses, packaging)
- Passive Devices (filters, radiators)
- Active Devices (Silicon versus III-V)
- Integration/Packaging Techniques
  - Antenna In Package
  - Antenna on Chip
- Wideband Signal Processing
  - Challenges to achieve required BW, PAE, Linearity, Latency
  - Analog versus digital versus digital beamforming
  - Massive MIMO
- mm-wave testing challenges
  - More integration means less known-good dies – yield concerns
  - Over the Air (OTA) Testing and Calibration
- Materials Characteristics
  - Frequency/Phase Stable (uniform/isotropic D_k)
  - Loss Performance
  - Processability

[18] http://soiconsortium.eu/wp-content/uploads/2018/08/SOI-Consortium-Sept-2018-RFSOI-Day-2-PRabbeni.pdf

TRX Requirements

- Power
- Linearity
- Robustness
- Efficiency
- Integration
- Cost

- What are the supply chain issues?
- Access to the most advanced technology but on-shore in low volumes
- Parts obsolescence, security, industry support
- Possible solutions: standardized interfaces, IP-Reuse ecosystem

5.2 What are Interdisciplinary Challenges

- Tight integration of mm-wave active electronics, filters, and antenna is critical to 5G RF Front-Ends
- Multilayer fabrication with fine geometry and accurate alignment
- Metallization with smooth and well-defined surface and near-vertical edge
- Compatible coefficient of thermal expansion (CTE)
- Novel Materials – better electrical, microwave and thermal properties at a low cost
- Precise IC/SMT mounting pedestal or pocket formation
- Novel circuit design and thermal management techniques
- Multi-physics analysis/modeling: simulation for mechanical, thermal, optical, electrical
- Co-Simulation of package, circuit and device – including circuit, EM and thermal analysis

5.3 Current Development in Heterogeneous Integration for 5G

Figures 5-1 and 5-2 from Yole summarizes the status of advanced substrate technology and flip-chip and fan-out packaging. For 5G millimeter-wave FEMs operating between 25 and 40 GHz, designers will take advantage of monolithic integration of functions enabled by CMOS and Fully-Depleted Silicon on Insulator (FD-SOI) to put analog, RF and digital IP blocks into a System on a Chip (SOC). Since digital I/O requires many pins, (100's to 1000's), there will be the need for finer-pitch I/O between the chip and the package. Therefore, linewidth and spacing needs for 5G SOCs will be enabled by reduction of 5/5 L/S to 2/2 by 2025 and down to 1/1 by 2030.

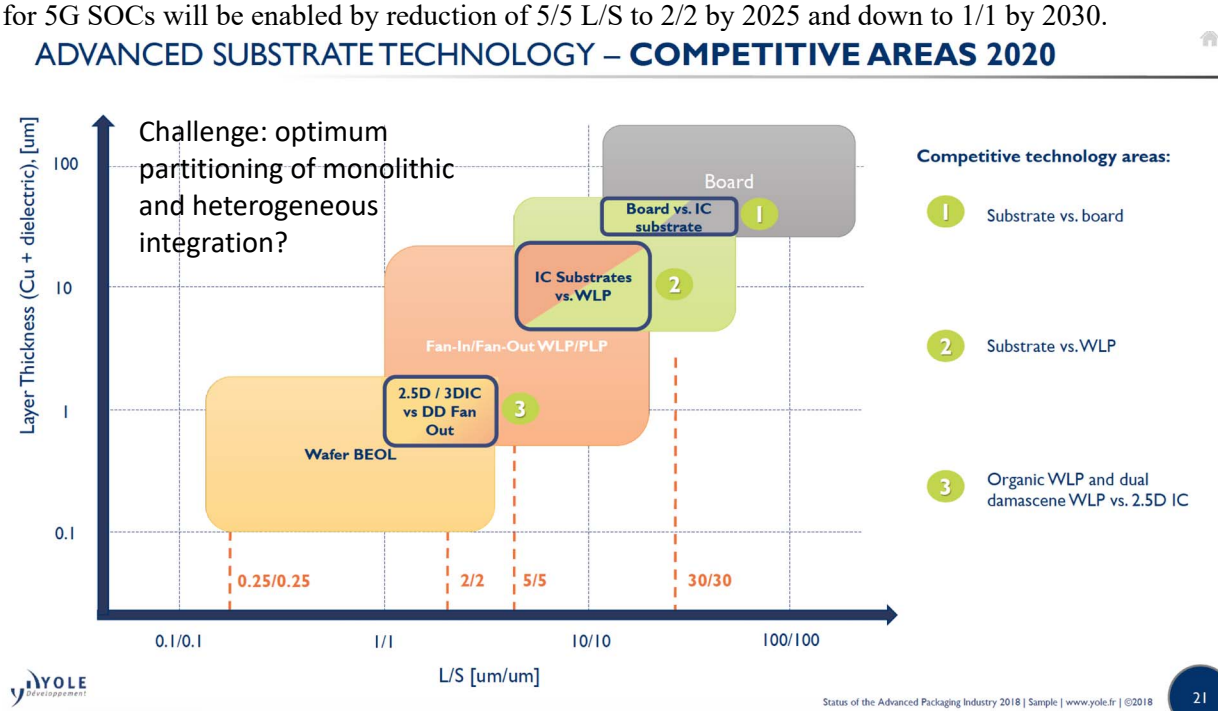


Figure 5-1. Advanced Substrate Technologies Suitable for 5G (Yole[19])

[19] http://www.yole.fr/AdvancedSubstrates_AdvPackaging_Platforms.aspx#.XQ_byXt7muU

As shown in Figure 5-3, there will be opportunity for the optimization of SiP architectures for below-6 GHz and millimeter-waves. The current "sweet" spot for 4G LTE FEM uses flip-chip and Fanout WLP. Therefore, it makes sense that these capability providers continue to advance their offerings to finer pitch and thinner substrates that would support tight integration of actives and the antenna element. There should be opportunity for glass substrates since glass offers the lowest insertion loss and has excellent surface roughness. Similar opportunities may be available for flex substrates.[20]

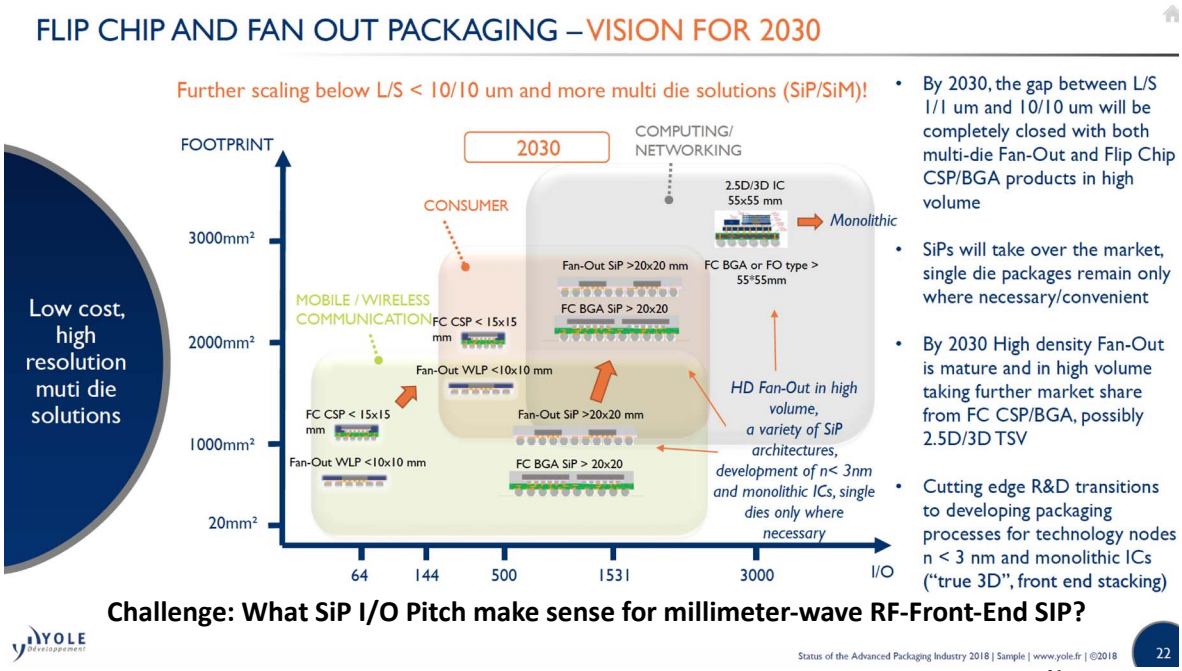


Figure 5-2. What SiP I/O Pitches make sense for millimeter-wave RF-Front-End SiP?[21]

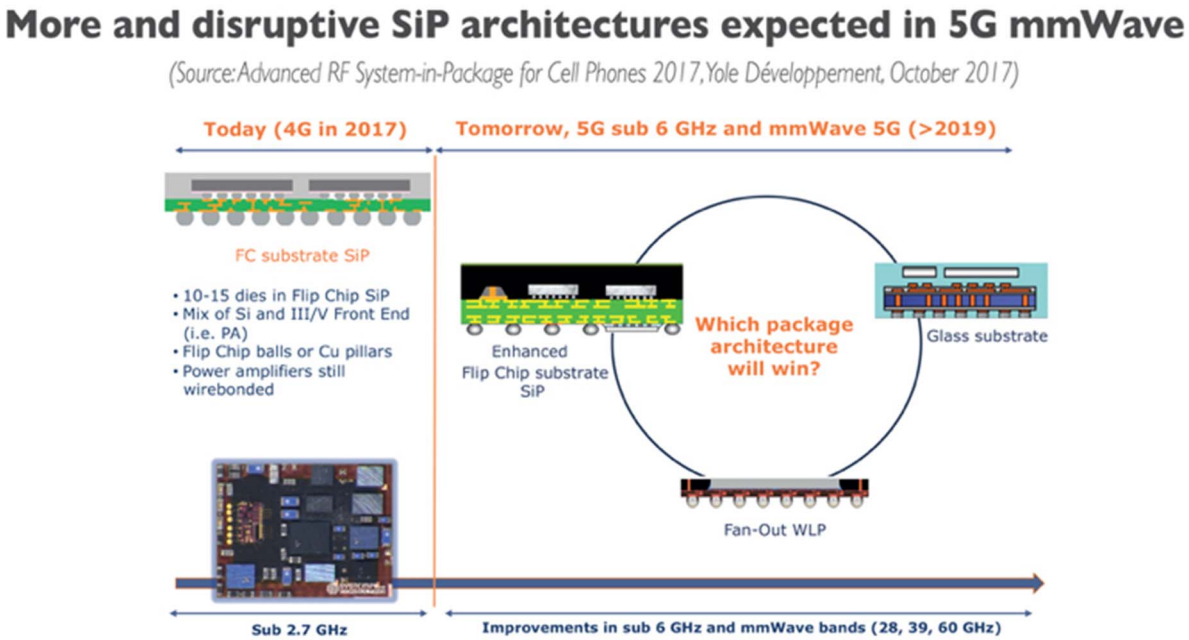


Figure 5-3. Disruptive SiP Architectures expected in 5G mmWave. (Yole[22]*)*

[20] DOW, "Why Flex Matters," http://www.ocipcdc.org/archive/Jonathan_Weldon_Flex_for_5G_Why_Materials_Matter_03292018.pdf
[21] http://www.yole.fr/AdvancedPackagingIndustry_MarketStatus.aspx#.XQ_cHnt7muU
[22] https://www.systemplus.fr/wp-content/uploads/2017/11/Yole_AdvancedRFSiPforCellPhones_Sample.pdf

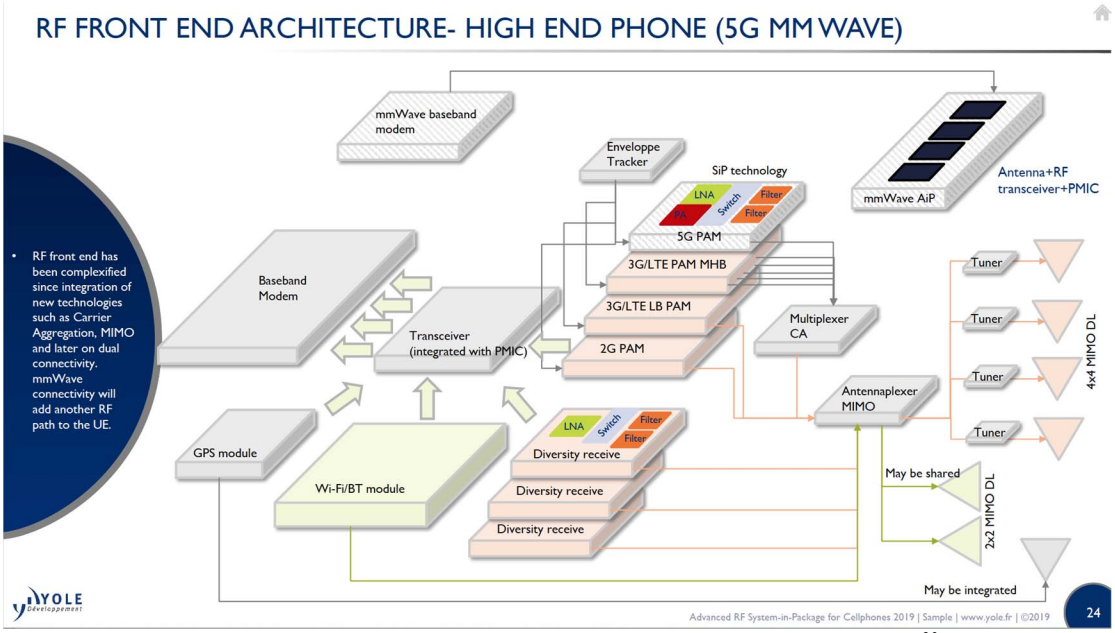


Figure 5-4. RF Front-End Architecture for High-End 5G Phone. (Yole[23])

5.4 Substrates and Materials for 5G

Figure 5-5 summarizes four different substrates that could be used for 5G: LTCC, low-loss laminates, Fanout WLP and glass. Each of these substrates has merit and will compete for usage in both below-6 GHz and millimeter-wave applications. Factors that will decide which are successful include microwave properties, costs, manufacturing yields and scalability to high volumes with good thermal and reliability characteristics. Figure 5-6 compares the substrate material properties of glass, LTCC, FR4 and LCP as compared to silicon. All four substrates have big CTE mismatches compared to silicon and therefore the packaging technology and processes must address solder joint reliability and the need for underfill.

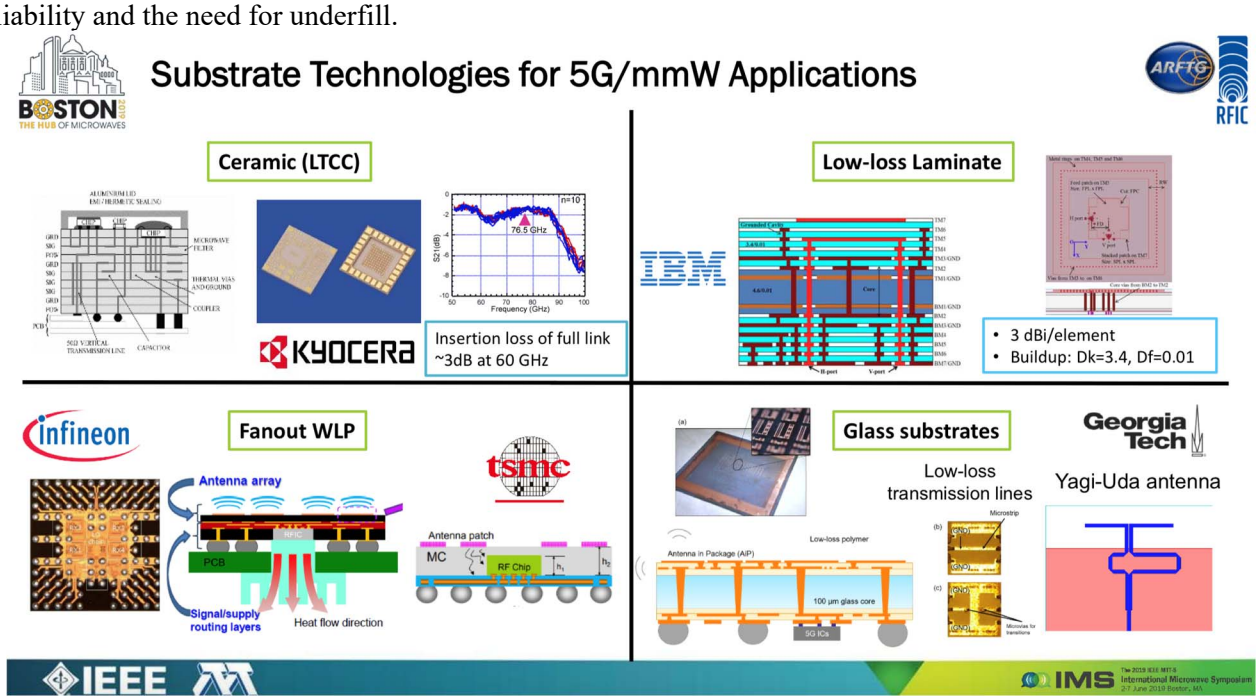


Figure 5-5. Comparison of Substrate Technologies for 5G/millimeter-wave applications (GaTech, IMS2019 Workshop[24])

[23] https://www.slideshare.net/Yole_Developpement/advanced-rf-systeminpackage-for-cellphones-2019

[24] Madhavan Swaminathan, IMS2019 Workshop: WMG-3: "Design and Fabrication of SIW at mm-Wave using Organic Substrates"

Substrate Materials

	Photo Definable Glass	Silicon	LTCC	FR4	LCP
CTE [ppm]	7.5-10	2.6	5.9-10	15	17 (CTE_z=150)
Dielectric Constant	5.7	11.7	5.9-8	4.7	2.2-3.2
Tg [^{o}C]	450	N/A	N/A	110-200	280-250
Young's modulus [Gpa]	81		12-27	17	
Manufacturing	Semiconductor	Semiconductor	Screen-printing	Subtractive/ Additive	Subtractive/ Additive
Drill Size [um]	Very small	small	large	large	large
Layer thickness [um]	<100	<100	<100	40	25

Figure 5-6. Comparison of Substrate Materials (Intel[25])

Figure 5-7 highlights where glass is superior for millimeter-waves: for high performance low-loss low-pass and band-pass filters. Glass has D_k of 3.3, D_f of 0.0044 and is stable up to at least 50 GHz. Figure 5-8 shows some test results of 30-GHz filters fabricated on glass substrates.

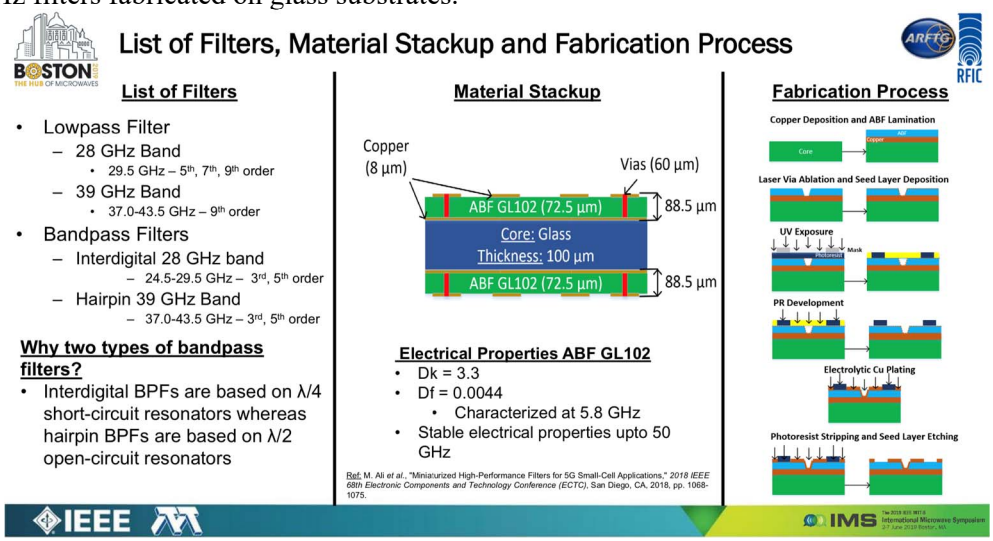


Figure 5-7. Use of Glass Substrates for Low-Loss millimeter-wave Filters (GaTech, IMS2019 Workshop)

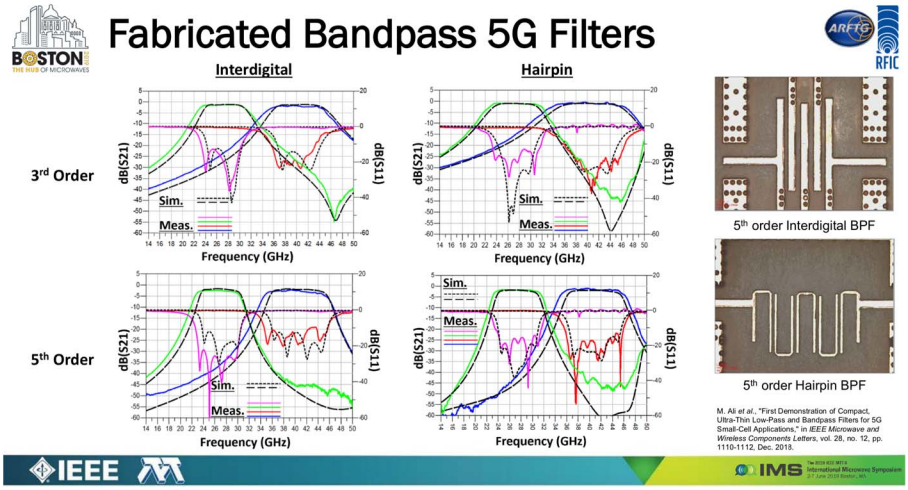


Figure 5-8. High Performance Bandpass Filters at 28- and 39 GHz Demonstrate How 5G RFFE requirements can be achieved (GaTech, IMS2019 Workshop)

[25] Telesphor Kamgaing, IMS2019 Workshop: WSC-7: "Millimeter Wave Packaging and Antenna Integration for 5G Applications and Beyond"

Figures 5-9 and 5-10 highlight the advantages of flex substrates, comparing the properties of polyimide to more well-known liquid crystal polymer (LCP). According to Dow, flex materials are glass-free with low D_k and D_f as compared to glass epoxy. Processability of polyimide may be superior to LCP due to stability at lamination temperatures and high peel strength.

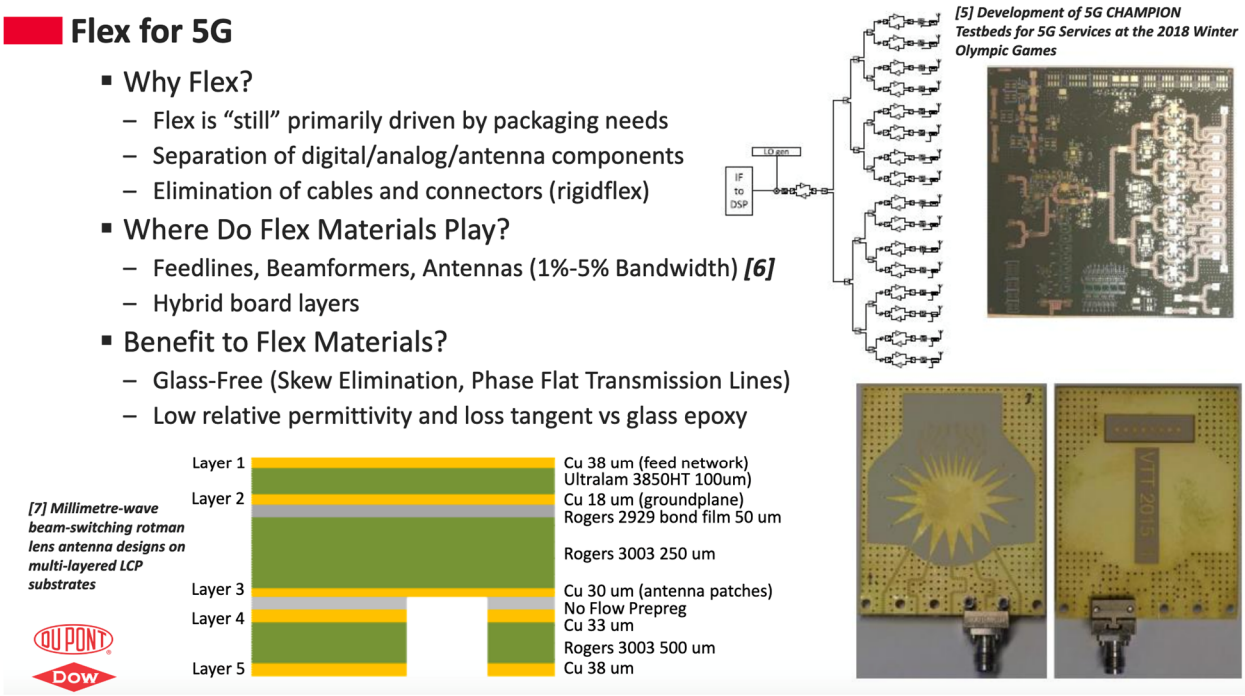
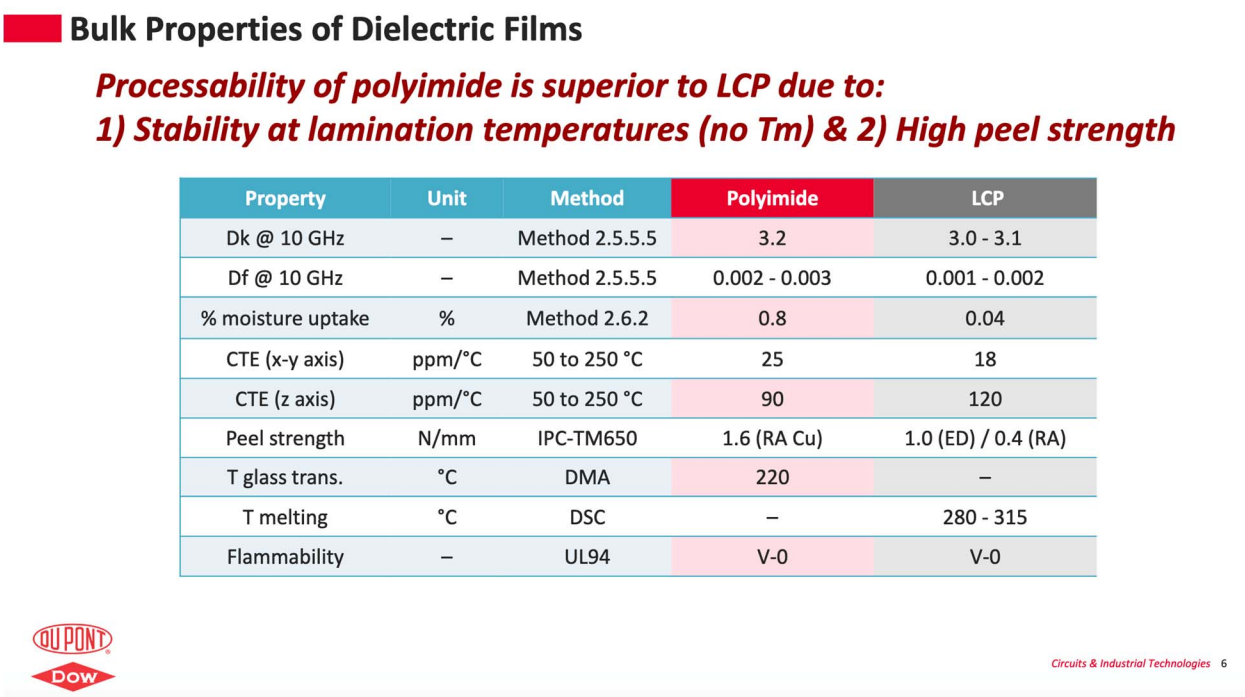


Figure 5-9. Flexible Substrates Offer Low-Loss Material for 5G Applications (Dow[15])



Property	Unit	Method	Polyimide	LCP
Dk @ 10 GHz	–	Method 2.5.5.5	3.2	3.0 - 3.1
Df @ 10 GHz	–	Method 2.5.5.5	0.002 - 0.003	0.001 - 0.002
% moisture uptake	%	Method 2.6.2	0.8	0.04
CTE (x-y axis)	ppm/°C	50 to 250 °C	25	18
CTE (z axis)	ppm/°C	50 to 250 °C	90	120
Peel strength	N/mm	IPC-TM650	1.6 (RA Cu)	1.0 (ED) / 0.4 (RA)
T glass trans.	°C	DMA	220	–
T melting	°C	DSC	–	280 - 315
Flammability	–	UL94	V-0	V-0

Figure 5-10. Comparison of Polyimide versus LCP for Flex Substrates for Processability (Dow[15])

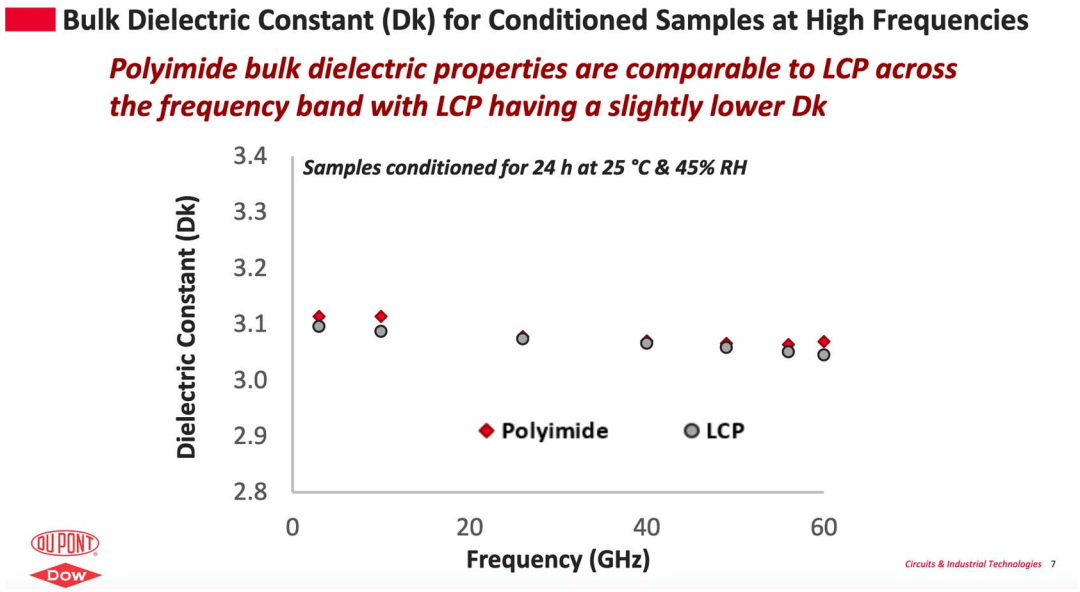


Figure 5-11. Comparison of Bulk Dielectric Constant (D_k) for Polyimide and LCP (DOW[15])

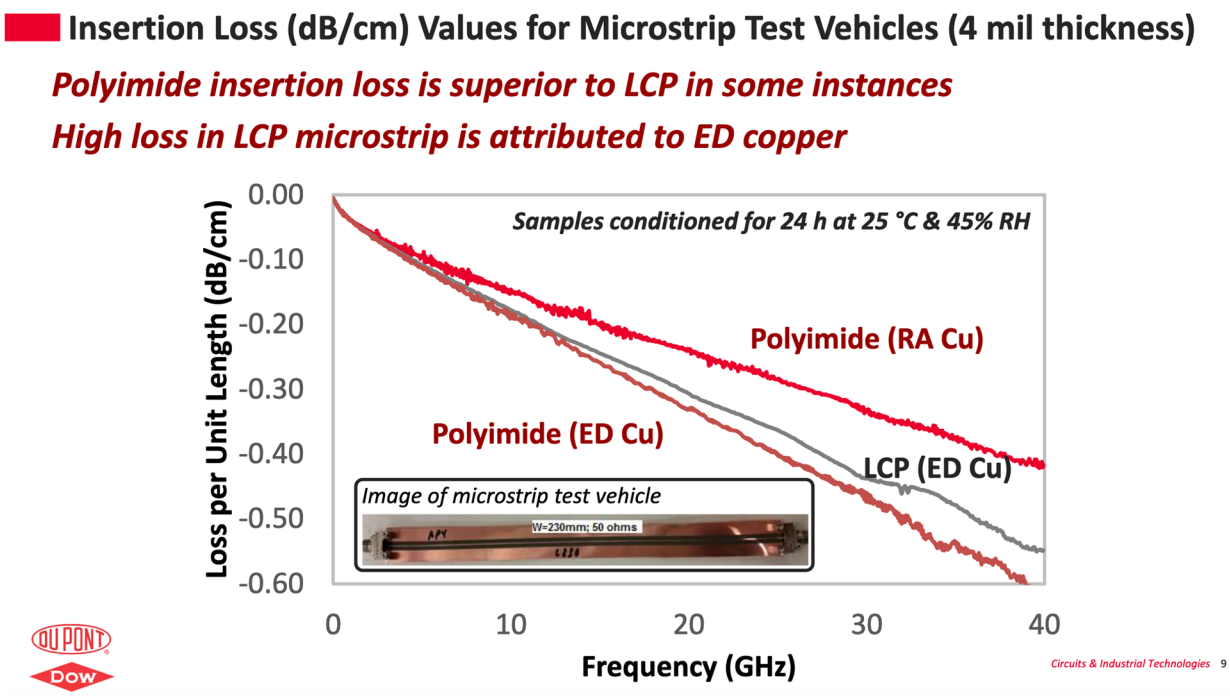


Figure 5-12. Comparison of Insertion Loss (dB/cm) for Microstrip for Polyimide versus LCP (DOW[15])

Figure 5-13 shows an example of laminate boards being used to integrate a 28-GHz beamforming phased array with work done at UCSD (G. Rebeiz).

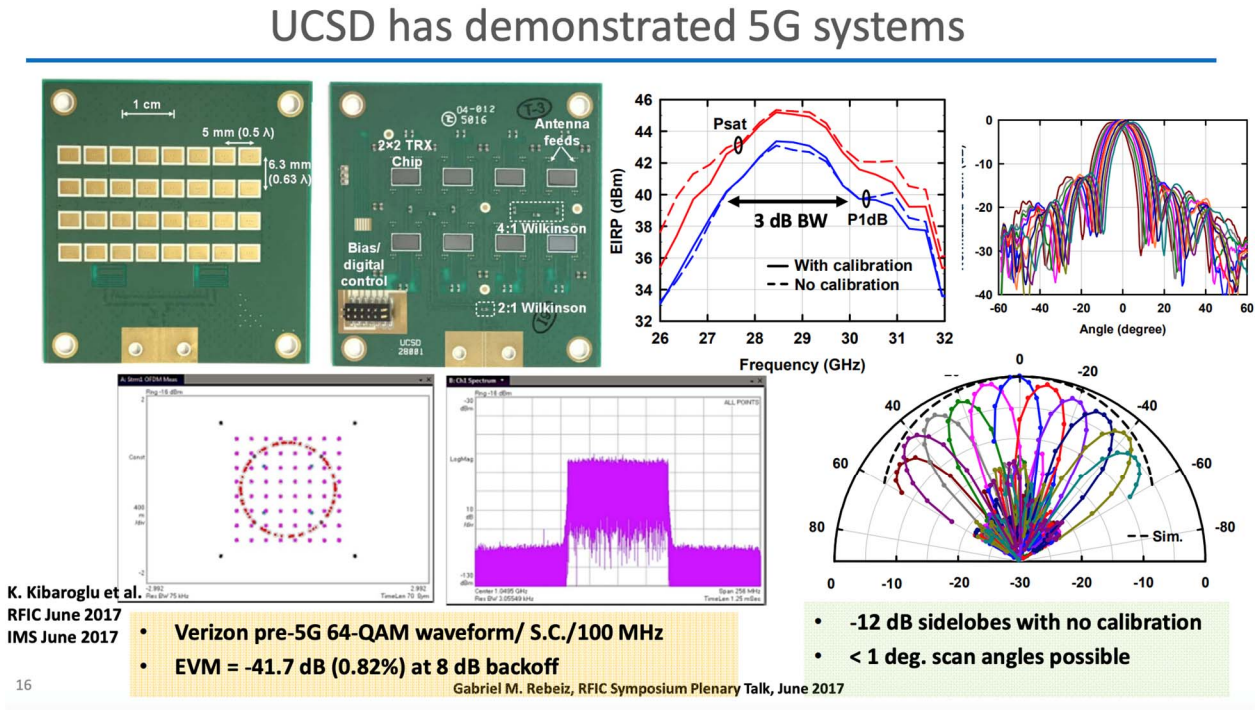


Figure 5-13. Demonstration of 28-GHz Phased Array Using Conventional PCB for Small Cell Form Factor (UCSD)

Georgia Tech has completed a study of substrate technologies for 5G.[26] In this research work, the author has collected a number of useful materials and properties of substrates and buildup materials with characteristics that are relevant at 5G millimeter-wave bands. Table 5-1 summarizes the Glass Core Materials and Properties; Table 5-2 summarizes the LTCC Core Materials and Properties; and Table 5-3 the laminates Materials and Properties. Table 5-4 and Table 5-5 lists the buildup (prepreg) and thin films Materials and Properties. Finally, Table 5-6 gives a comprehensive summary of design rules for each kind of substrate. These data tables are representative of today's technologies. The actual performance of the substrates and materials at 28- and 38-GHz must be demonstrated through simulation, fabrication and test.

Table 5-1. Glass Core Materials and Properties (GaTech, Ali)

Glass	Dielectric Constant	Loss Tangent
Corning SGW 3	5.15 @ 10 GHz	0.007 @ 10 GHz
(Low CTE alkali-free)		
Corning SGW8.5	6.9 @ 1 GHz	0.023 @ 10 GHz
(High CTE with alkali)		
AGC EN-A1	4.9 @ 10 GHz	0.0056 @ 10 GHz
Schott AF-32 eco	5.1 @ 5 GHz	0.0049 @ 5 GHz
Schott MEMpax	4.4 @ 5 GHz	0.0073 @ 5 GHz
Asahi Glass low loss	5.41 @ 35 GHz	0.0090 @ 35 GHz

[26] M. Ali, "Advanced 5G Substrates with Integrated Antennas," MS Thesis, GaTech, https://smartech.gatech.edu/bitstream/handle/1853/58327/ALI-THESIS-2017.pdf

Table 5-2. LTCC Core Materials and Properties (GaTech, Ali)

LTCC	Dielectric Constant	Loss Tangent	Operating Frequency	Conductor
Dupont 9K7	7.1 ±0.2	0.001	Up to 100 GHz	Silver, Copper
Ferro A6-S	5.9±0.2	0.001	Up to 100 GHz	Silver
DP943	7.4	0.002	Up to 40 GHz	Silver
DP951	7.8	0.014	Up to 40 GHz	Silver
NGK-NTK NOC-F1	6.0	0.0021	Up to 60 GHz	Copper
Hitachi Metals LTCC*	8.13	0.00086	Up to 14 GHz	Silver
TDK-Epcos*	-	Low Loss	-	Copper

Table 5-3. Laminates Core Material and Properties (GaTech, Ali)

Material Laminate	D_k				D_f			
	10 GHz	28 GHz	38 GHz	45 GHz	10 GHz	28 GHz	38 GHz	45 GHz
MGC BT Laminate		3.400	3.400	3.400	0.0040	0.0040	0.0041	0.0043
Panasonic Megtron 7	3.600	3.600	3.600	3.600	0.0040	0.0040	0.0040	0.0050
Rogers RO4350B	3.730	3.715	3.710	3.700	0.0037	0.0039	0.0039	0.0040
Rogers RO 4350B LoPro	3.640	3.630	3.620	3.600	0.0037	0.0039	0.0039	0.0040
Rogers RO4003C	3.650	3.640	3.635	3.630	0.0027	0.0028	0.0028	0.0029
Rogers RO4003C LoPro	3.525	3.520	3.520	3.510	0.0027	0.0028	0.0028	0.0029
Rogers RO4725JXR	2.55	-	-	-	0.0026	-	-	-
Rogers	3.0	-	-	-	0.0027	-	-	-
RO4730G3								
MGC HL972LF (LD)	3.4	3.4	3.4	3.37	0.004	0.004	0.004	0.004
Hitachi LW900G	3.6	-	-	-	0.0044	-	-	-
Hitachi LW910G	3.3	-	-	-	0.003	-	-	-
Panasonic	3.65	-	-	-	0.004	-	-	-
R-G545 (R&D)								
Panasonic	3.4	-	-	-	0.003	-	-	-
R-G545 Low Loss (R&D)								

Table 5-4. Buildup Material – Prepreg (GaTech, Ali)

Material Prepreg	D_k				D_f			
	10 GHz	28 GHz	38 GHz	45 GHz	10 GHz	28 GHz	38 GHz	45 GHz
Panasonic Prepreg R-5670(K)	3.220	3.220	3.220	3.220	0.0050	0.0050	0.0050	0.0060
Panasonic Prepreg R-5680 Low-D_k Glass	3.110	3.110	3.110	3.110	0.0020	0.0020	0.0020	0.0030
Panasonic R-G540	3.65	-	-	-	0.004	-	-	-
Panasonic R-G540 Low Loss	3.4	-	-	-	0.003	-	-	-
Rogers RO4450F Prepreg	3.52	-	-	-	0.004	-	-	-
Hitachi LW900G Prepreg	3.2	-	-	-	0.004	-	-	-
Hitachi LW910G Prepreg	3.1	-	-	-	0.0025	-	-	-
Hitachi HS100 Prepreg	3.4	-	-	-	0.0045	-	-	-
Hitachi HS100(E) Prepreg	3.2	-	-	-	0.003	-	-	-
Hitachi GWA900G	3.37	-	-	-	0.0024	-	-	-

Table 5-5. Buildup Materials – Films (GaTech, Ali)

Material Films	D_k				D_f			
	10 GHz	28 GHz	38 GHz	45 GHz	10 GHz	28 GHz	38 GHz	45 GHz
Rogers 2929	2.940	2.940	2.940	2.940	0.0030	0.0030	0.0031	0.0031
ABF GY-11	3.200	3.200	3.200	3.200	0.0042	0.0043	0.0043	0.0044
Hitachi Chemical AS-500S	3.500	3.500	3.500	3.500	0.0030	0.0030	0.0031	0.0032
Dow 14-P005 BCB Dry Film[1]	2.65	-	-	-	0.0015	-	-	-
New ABF Low Loss Film2	3.2	3.2	3.2	3.2	0.0042	0.0043	0.0043	0.0044
JSR New Low Loss Polymer	2.46 – 2.67	-	-	-	0.0027 – 0.008	-	-	-
Rogers XP	2.6	2.6	2.6	2.6	0.0023	-	-	Expect to be flat

The GaTech study recommends the follow substrates for consideration for 5G:

Low-loss RDL on Laminates:

- Core: Rogers RO4725JXR and RO4830
- RDL: Rogers XP film, ABF GY-11/GL-102

Low-loss RDL on Glass:

- Core: Standard 100µm AGC glass with loss tangent of 0.005 at 10 GHz
- RDL: Rogers XP film, ABF GY-11/GL-102

Low-loss RDL on Ceramic:

- Low-loss Cu-Polymer RDL on TDK-Epcos LTCC
- RDL: Same material options as Laminate and Glass

The rationale for choosing Rogers RO4725JXR and RO4830:

- Low D_k and D_f at 37 GHz and 127µm thickness
- Stability of electrical properties at higher frequencies
- Easier Processability

Table 5-6. Design Rule Summary (GaTech)

Material	Panel Size (R&D, Mfg.)	Core Via Dia.	Core Via Pitch	RDL L/S	LW Tolerance	RDL Via Dia.	Layer Count
Laminates	510mm x 510mm (IC Sub)	40 µm	>100 µm	30/30 standard	10-20%	N/A	High (>10)
(PWB)	900mm x 1200mm (PWB)			15/15 advanced			
RDL on Laminate	Mfg	-	8/8 standard	-	30mm standard	Up to 6 each side typical	
			2/2 µm advanced		10 µm advanced		
LTCC Core	200mm x 200mm Standard	60 µm	120 µm	50/50 standard	<5%	-	High
	300mm x 300mm Limited Availability	Typ.	Typ.	30/30 advanced			(4-20)
RDL on LTCC	-	-	2/2 µm	TBD	10 µm	3 (top side only)	
					20µm pitch		
Glass	150mm x 150mm (GT 2016)	25 µm	50 µm	2/2 µm	±2% (Target)	5 µm	6-8 (double side)
	300mm x 300mm (GT 2017)					20 µm pitch	
	510 mm x 510 mm (Mfg TBD)	(R&D)	(R&D)				

5.5 Antenna in Package versus Antenna on Chip

This section introduces the trade-off between Antenna in Package (AiP) versus Antenna on Chip (AoC).

- **Antenna on Chip**: (AoC)
  - Advantages: Absence of any RF interconnect and the co-integration of all RF and baseband functions on a single module; very small (few square millimeters)
  - Cons: For silicon-based AoCs, high permittivity (ε_r = 11.7 to 11.9) and low resistivity ($\rho \sim 10\ \Omega$-cm) of the substrate severely degrade the matching bandwidth and radiation efficiency.
- **Antenna in Package** (AiP)
  - Advantages: Realized on a separate substrate, independent of the RFIC chip. This substrate can either be specifically dedicated to the radiating element and its feeding lines or play the role of a package for transceiver assembly and heterogeneous integration.
  - AiP, using 3D integration for millimeter-wave transceivers, will provide additional degrees of freedom with the choice of low permittivity and/or high resistivity substrates.

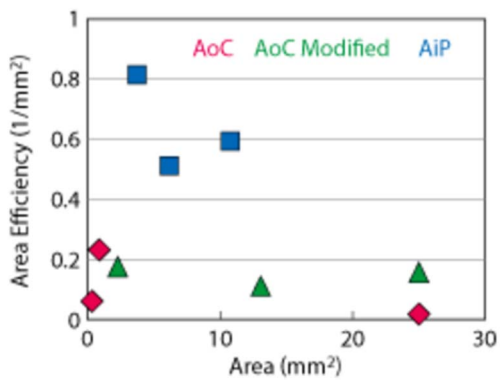


Figure 5-14. Trade-off Between AoC and AiP[27]

Figure 5-15 provides an excellent overview of AiP assembly technology, as presented by ASE in the IMS2019 Workshop. Important criteria for AiP processes include Low D_k/D_f, dimensional control, warpage control, realization of antenna circuit, and thermal/reliability concerns. Figure 5-16 projects the technology trends for AiP development. As the 5G operating bands continue to rise from 28-, 39-, 60-, 77- and beyond 90 GHz, the substrate thickness must become thinner. It is expected that the current 1.6mm thickness will have to be reduced to half of what it is today – ~0.7 to 0.8 mm. Process control for warpage, dimensional control and reliability all have to be improved. Figure 5-17 shows examples of current AiP substrates that are achieving good performance at 28 and 38 GHz with excellent alignment stacking and dimensional control.

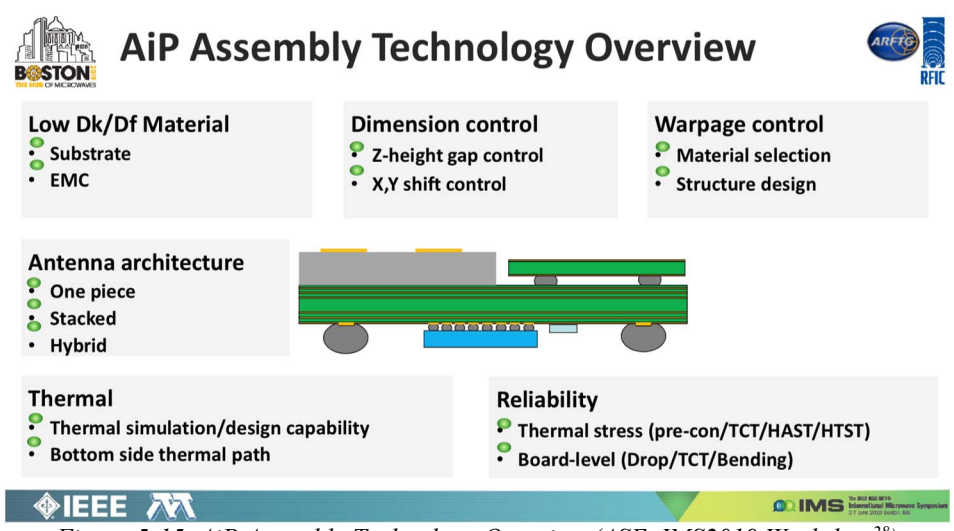


Figure 5-15. AiP Assembly Technology Overview (ASE, IMS2019 Workshop[28]*)*

[27] https://www.signalintegrityjournal.com/articles/46-d-integration-and-packaging-of-mmwave-circuits-and-antennas-opportunities-and-challenges

[28] Harrison Chang, IMS2019 WMG-5: "Characterization of Low-Cost Organic Substrate for mm-Wave AiP Applications"

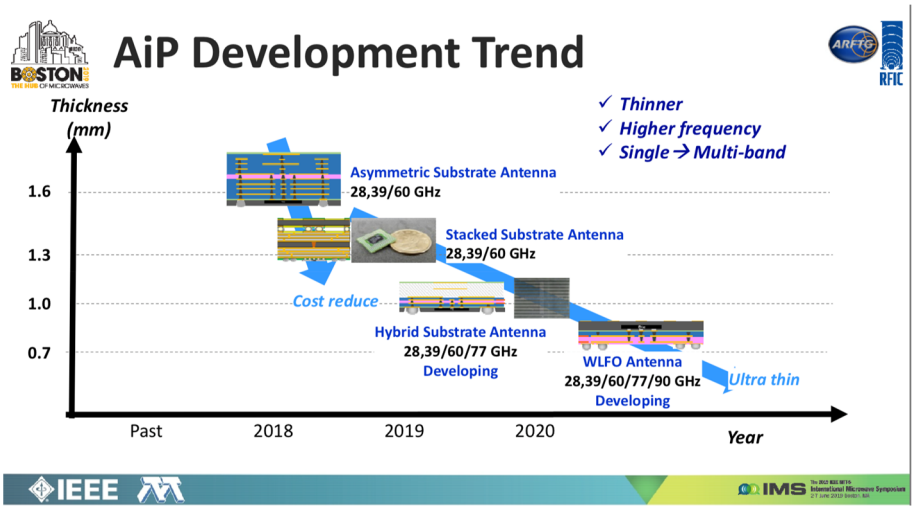


Figure 5-16. AiP Development Trend – Thinner Substrates will be needed for high frequencies (ASE, IMS2019 Workshop)

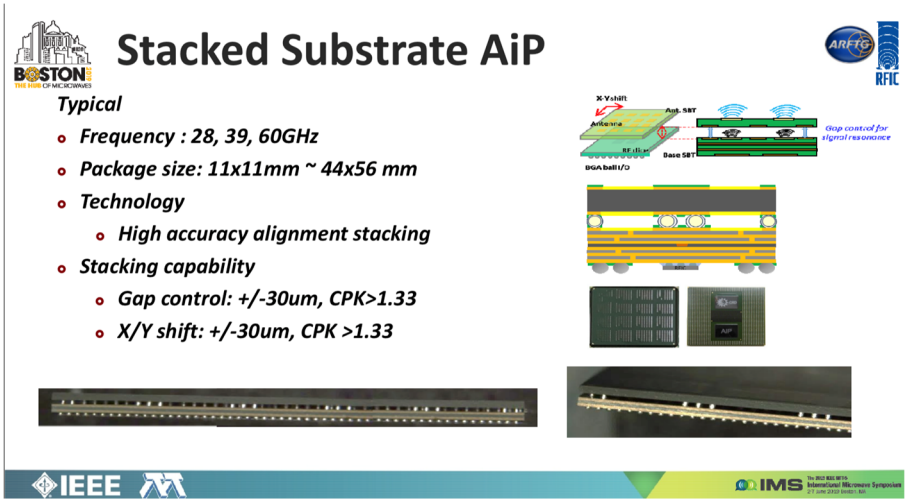


Figure 5-17. Stacked Substrate AiP Supports 28-, 39- and 60 GHz with excellent gap control and alignment (ASE, IMS2019 Workshop)

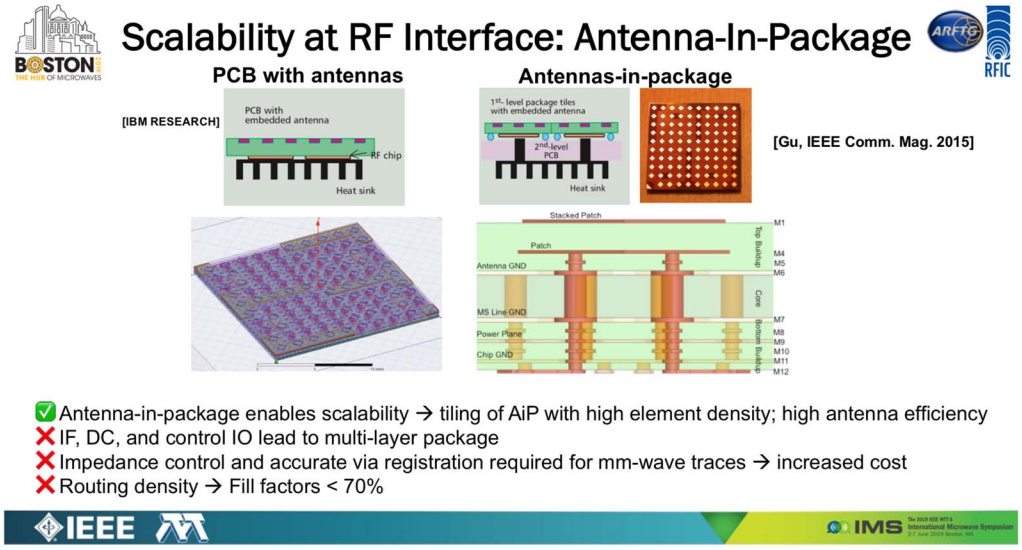


Figure 5-18. Scalability at RF Interface: Antenna-In-Package (OSU[29])

[29] Y. Liu, IMS2019 WSC-1: "Antenna-IC Interfaces for Scalable mm-Wave Arrays for 5G and Beyond-5G Applications"

Figure 5-18 looks at the scalability at the RF interface for the Antenna-in-Package approach. AiP offers the ability to achieve high element density. Figure 5-19 presents some challenges for Antenna-On-Chip: poor efficiency for topside radiation. The use of high-resistivity substrates is needed to cover excess losses. Other researchers indicate that AoC would be an attractive option at frequencies above 100 GHz to perhaps as high as 1 THz. Figure 5-20 summarizes antenna array scalability challenges for frequencies higher than 60 GHz.

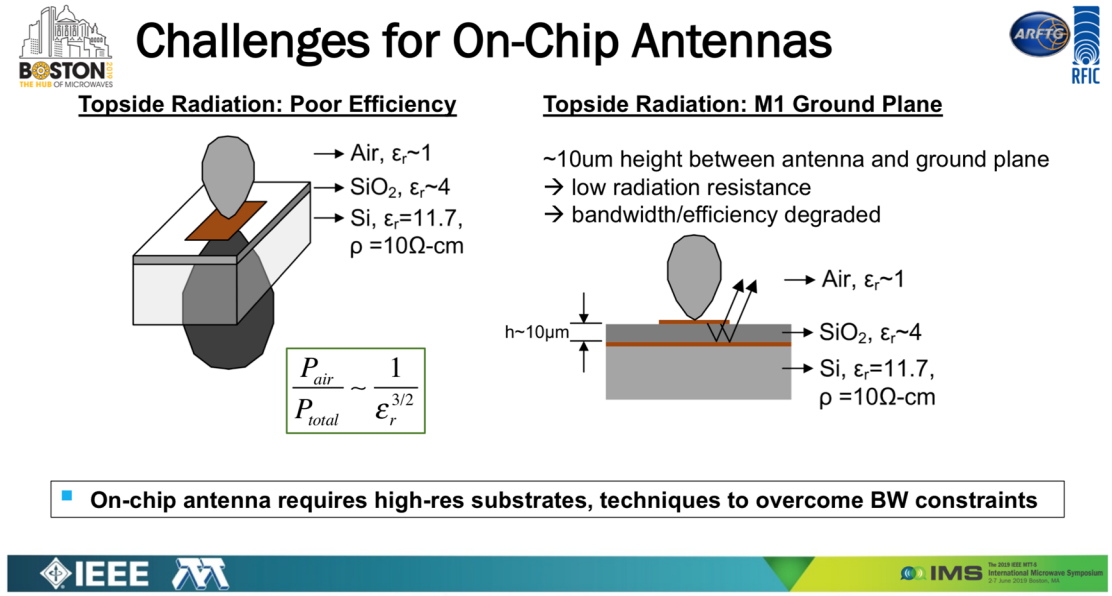
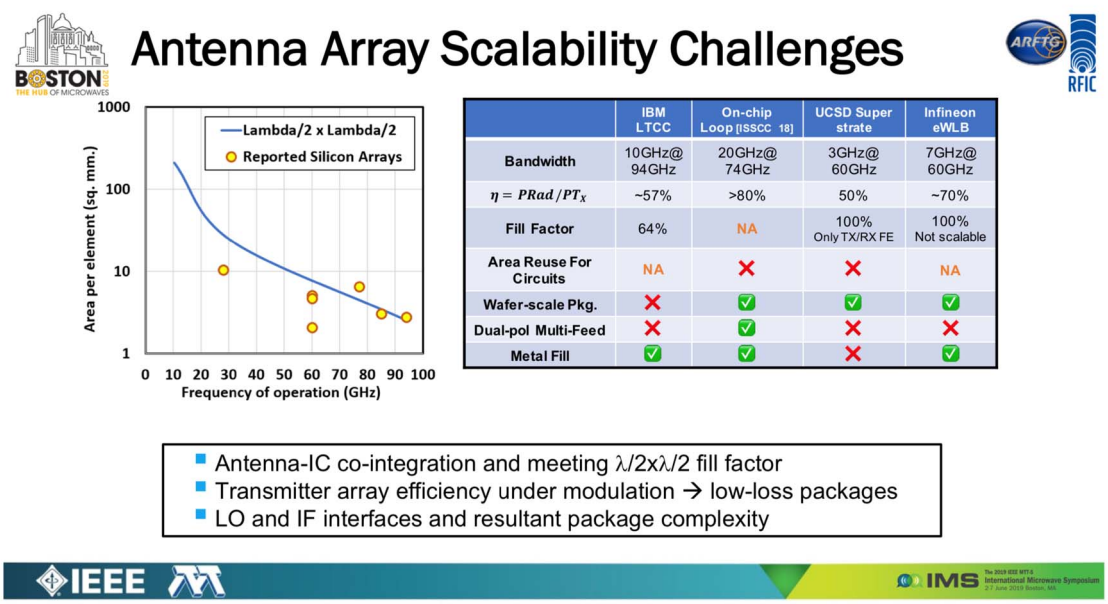


Figure 5-19. Challenges for On-Chip Antennas (OSU)



	IBM LTCC	On-chip Loop [ISSCC 18]	UCSD Super strate	Infineon eWLB
Bandwidth	10GHz@ 94GHz	20GHz@ 74GHz	3GHz@ 60GHz	7GHz@ 60GHz
$\eta = PRad/PT_X$	~57%	>80%	50%	~70%
Fill Factor	64%	NA	100% Only TX/RX FE	100% Not scalable
Area Reuse For Circuits	NA	✗	✗	NA
Wafer-scale Pkg.	✗	✓	✓	✓
Dual-pol Multi-Feed	✗	✓	✗	✗
Metal Fill	✓	✓	✗	✓

Figure 5-20. Antenna Array Scalability Challenges (OSU)

5.6 Examples of Highly Integrated AiP-based Millimeter-Wave 5G Phased Arrays

Figure 5-21 and Figure 5-22 shows examples of highly integrated AiP-based millimeter-wave 5G Phased Arrays with promising performance.

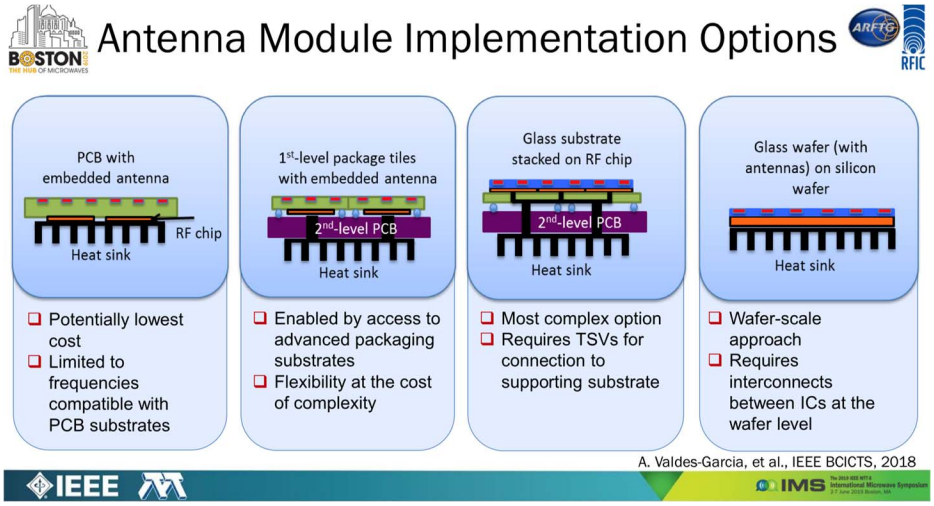


Figure 5-21. Antenna Module Implementation Options (IBM[30])

Key mmWave 5G pico cell challenges	Phased array IC design challenges	Antenna and package design challenges
Maximize TX range while minimizing form factor	Maximize TX output power, with TX/RX integration	Integrate multiple RFICs enabling array scalability
Ease of beam-forming and beam-control	Orthogonal phase and gain control at each front-end	Implement a wide-band antenna element with equal-length feed lines
High beam steering resolution over wide range scan range	Fine phase resolution in phase shifter	Balance antenna gain and element pattern; Maintain antenna uniformity
Support for simultaneous beams	Support for two polarizations at IC level	Support dual-polarized antennas and configurable beams at module level

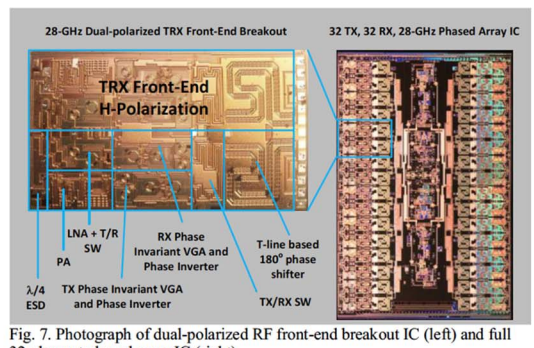


Fig. 7. Photograph of dual-polarized RF front-end breakout IC (left) and full 32-element phased array IC (right)

Figure 5-22. Antenna performance needs to be optimized for designed gain, BW and radiation patterns. (IBM[31])

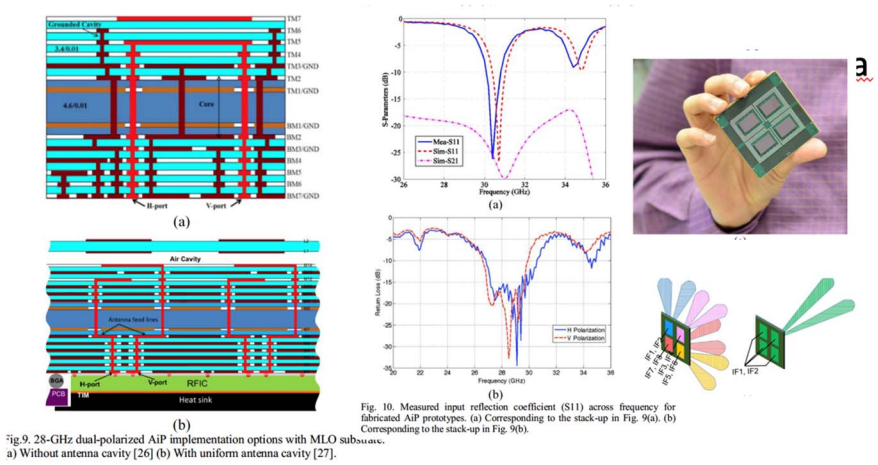


Fig.9. 28-GHz dual-polarized AiP implementation options with MLO substrate. a) Without antenna cavity [26] (b) With uniform antenna cavity [27].

Fig. 10. Measured input reflection coefficient (S11) across frequency for fabricated AiP prototypes. (a) Corresponding to the stack-up in Fig. 9(a). (b) Corresponding to the stack-up in Fig. 9(b).

Table III. Summary of Si-based TRX phased arrays for 5G at Ka-band demonstrated with on-board or in-package antennas

Reference	[28]	[32]	[33]	This work
Frequency (GHz)	29	29	28	28
# of elements per IC	4TRX	4TRX	8TRX	32TRX
# ICs in PAAM	8	1	1	4
# of concurrent TX/RX pol.	1	1	1	2
Phase resolution (°)	5.6	5.6	45	5
RMS phase error (°)	6	6	7	0.8
TX P_{sat} (dBm) per element	13	—	10.5	16
TX Op1dB (dBm) per element	11.7	10.5	—	13.5
TX power consumption per IC per pol. (W)	—	0.8 @oP1dB	0.68 @24dBm EIRP	4.6 5.1@Psat
RX power consumption per IC per pol. (W)	—	0.42	0.4	3.2
TX EIRP per module per pol. @Psat (dBm)	41	—	31.5	54
IC die area (mm²)	11.7	11.7	7.3	166
IC technology (nm)	180nm SiGe	180nm SiGe	28nm CMOS	130nm SiGe
Module Integration Approach	Ant. on PCB	Ant. on PCB	AiP	AiP

Figure 5-23. AiP mm-wave Considerations[32]

Figure 5-24 summarizes the AiP implement approach (InFO-AiP) which demonstrates that organic molded packages can be useful for 5G RF FEMs:

[30] IBM Research, Alberto Valdes-Garcia, "W-band antenna-in-package and phased array module integration for portable polarimetric imaging," IMS2019 Workshop WSC-5

[31] IBM Research, Alberto Valdes-Garcia, Bodhisatwa Sadhu et al, found at https://ieeexplore.ieee.org/document/8357050

[32] https://ieeexplore.ieee.org/document/8357050

- The InFO-AiP comprises an RF chip integrated in an InFO Molding Compound and antenna implemented in the RDL.
- The RF chip is interconnected to the RDL without using external bumps or solders balls.
- A novel slot-coupled antenna structure is adopted where the feeding line is placed in the RDL at the bottom of the package and coupled to the patch antenna which is designed on the top side of the package.
- Key Parameters and Features:
  - Surface roughness – losses at high frequencies
  - Interconnect Transition – controlled impedance
  - Slot-Coupled Patch Antenna

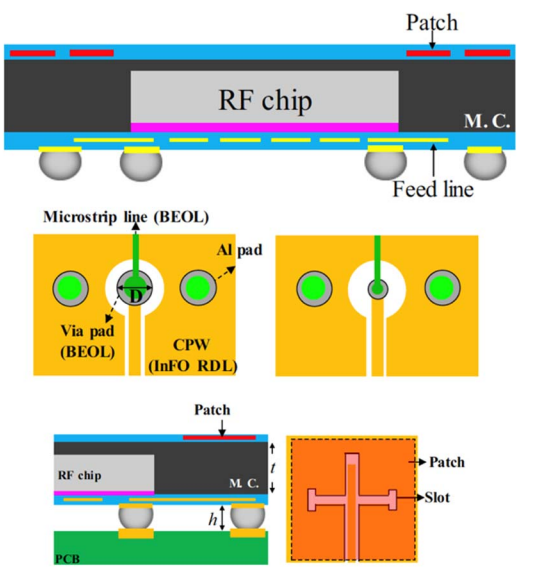


Figure 5-24. TSMC INFO-AIP for mm-wave 5G[33]

Figure 5-25 shows an advanced Thin-Profile Fan-Out package with demonstrated measured AiP results at 28 GHz. It has lower insertion loss as compared to FCBGA-based AiP.

Figure 5-26 shows INTEL's "Ultra Large Area SIPs and Integrated mmW Antenna Array Module for 5G mmWave Outdoor Applications" for small-cell BS applications.

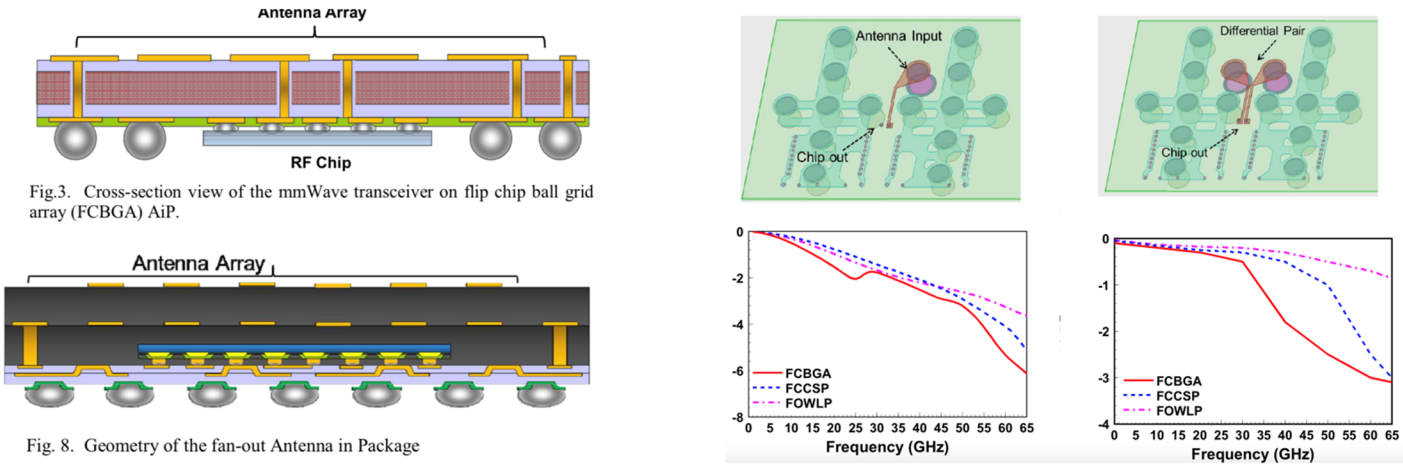


Figure 5-25. Advanced Thin-Profile Fan-Out with Beamforming Verification for 5G Wideband Antenna (ASE[34]*)*

[33] ECTC2018: https://ieeexplore.ieee.org/document/8429552
[34] Sheng-Chi Hsieh et al, ECTC2019, ASE

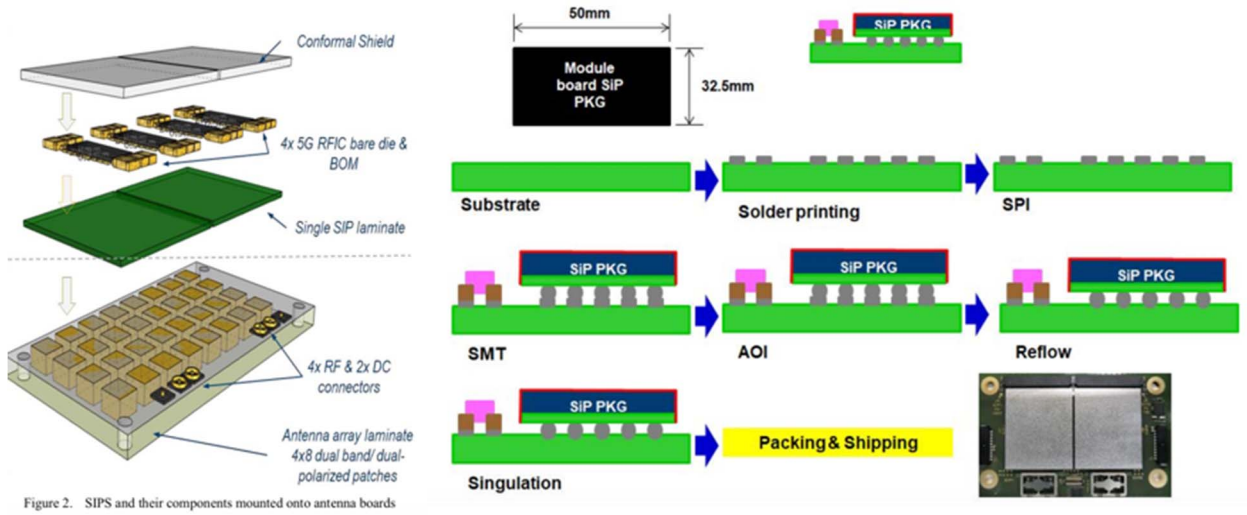


Figure 5-26. Ultra Large Area SIPs and Integrated mmW Antenna Array Module for 5G mmWave Outdoor Applications (INTEL[35])

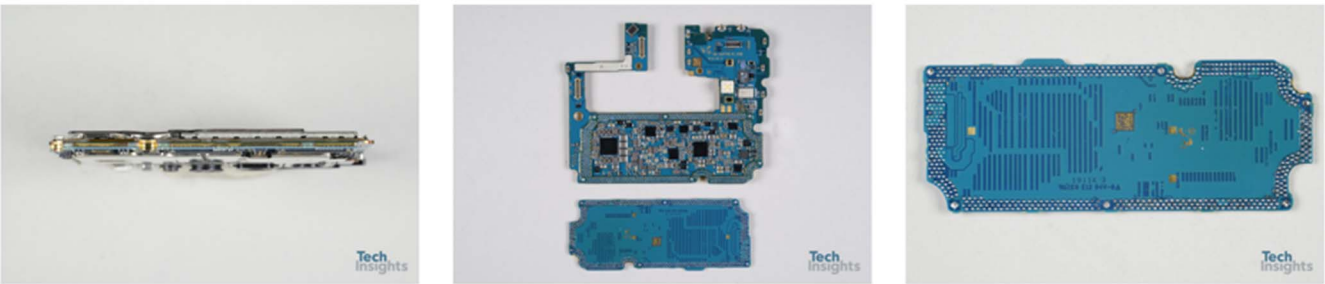
5.7 First 5G Phone Tear-Down

Figure 5-27 is a collage of tear-down photos of one of the first 5G phones available in mid 2019. It is interesting to see which packaging and assembly techniques are used. As more phones are released between now and 2020, the advanced packaging landscape for handsets will become clearer. There will be winners and losers. The initial versions do not necessary represent optimum solutions for performance, reliability, manufacturability and costs. As the 5G modem chipsets evolve, they will come with greater capabilities and demand additional packaging requirements.

5.8 5G Modem Status

The 5G Modem Status as of April 2019 is listed below:[36]

- Hi-Silicon (Huawei) announced its first generation 5G-only Balong 5G01 cellular modem and, more recently, its second-generation LTE/5G Balong 5000 cellular modem. A 5G version of its Kirin processor, the Kirin 990, is expected.
- Intel has announced the XMM8060 and XMM8160 cellular modems.
- Mediatek has announced the Helio M70 modem.
- Qualcomm has announced the Snapdragon 855 mobile platform and the Snapdragon X50 and X55 modems.
- Samsung has announced its Exynos 5100 (S5T5100) modem.



Details, next page

[35] Pouya Talebbeydokhti et al, ECTC2019, INTEL
[36] https://gsacom.com

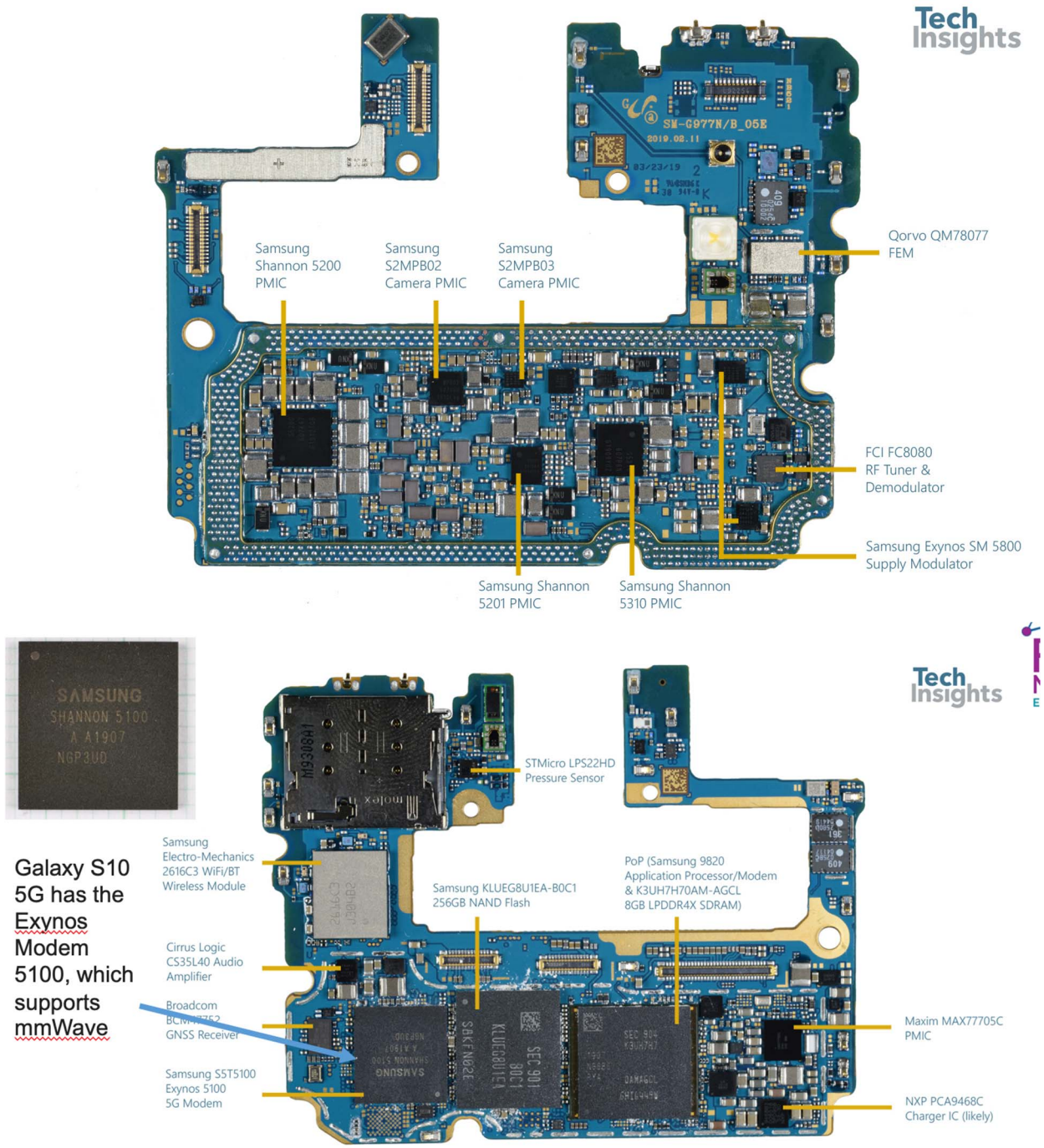


Figure 5-27. Teardown of Samsung S10 5G Smartphone (TechInSights[37])

6.0 6G – Beyond 10 years

6.1 6G Vision and Use Cases

Although 5G is just beginning deployment and probably will not have significant market penetration until 2025, thoughts are turning to what 6G would address. 3GPP will continue to advance wireless access beyond Rel. 15. Figure 6-1 provide a summary of the 3GPP timeline (2015-2023) for 5G releases.

[37] https://techinsights.com/blog/samsung-galaxy-s10-5g-teardown

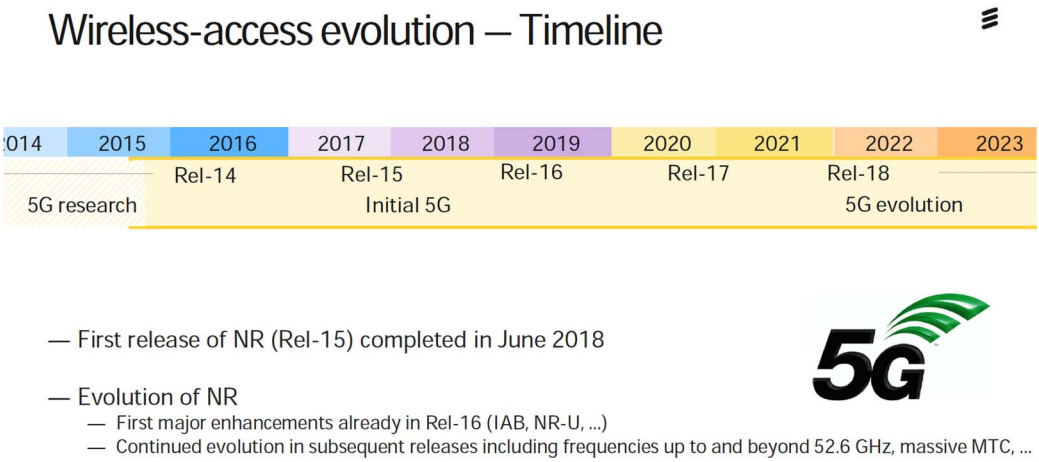


Figure 6-1. 3GPP Timeline to Evolve 5G and Beyond (Ericsson[38])

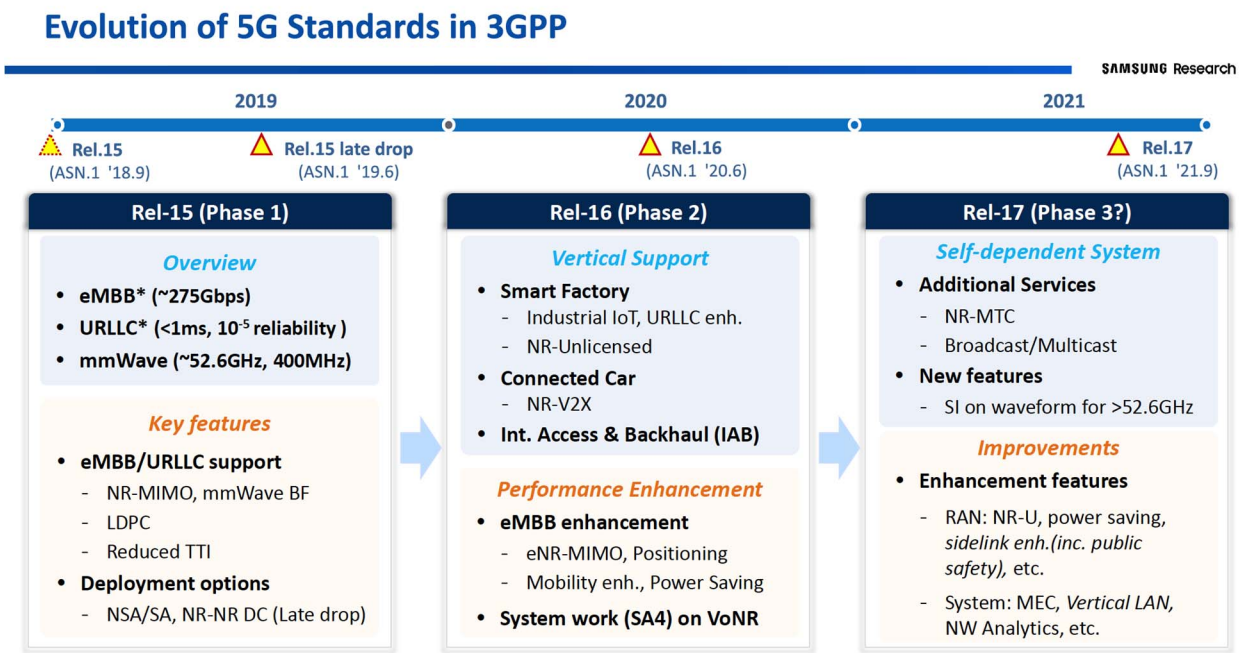


Figure 6-2. Evolution of 5G Standards in 3GPP (Samsung[39])

Features in NR Rel-16 include:

- Unlicensed Spectrum (LAA and stand-alone)
- V2X (Sidelink, Enhancements)
- Multi-Antenna Enhancements
- Integrated Access for BackHaul
- URLLC Enhancements
- Industrial IoT
- Remote Interference Management

Features being considered by NR Rel-17 include:

- Above 52.6 GHz
- Unlicensed 60 GHz
- IAB Enhancements
- Sidelink

[38] J. Peisa, "NR evolution – realizing the full potential of 5G," IEEE 6G Summit 2019, https://www.6gsummit.com
[39] Juho Lee, "Moving Towards 6G," IEEE 6G Summit 2019, https://www.6gsummit

- Non-terrestrial Access
- Drone Enhancements
- Multcast/Broadcast
- NR MTC for industrial service
- Reduced Complexity/Power Consumption

Longer-Term Evolution (> 10 years)

- Beyond 100 GHz
- Flexible Network Topologies
- Cellular as a Sensor
- Massive IoT (Trillions of devices)
- Device Cooperation
- Machine Learning/AI

Figures 6-3 and 6-4 show Samsung's perspective on 6G use cases, which include "Super-Enhanced Mobile Broadband," "Enhanced Latency," "Super-Precision Positioning" and massive connectivity exceeded 500B devices.

Finally, Figure 6-5 shows a modified 3GPP "triangle" diagram that projects the growth in all Use Cases:

- eMBB to Super eMBB
- URLLC to Super URLLC
- MM2M to Super MM2M

Of course, these are not official names for the 6G Use Cases. Ericsson also has a similar vision, as shown in Figure 6.6.

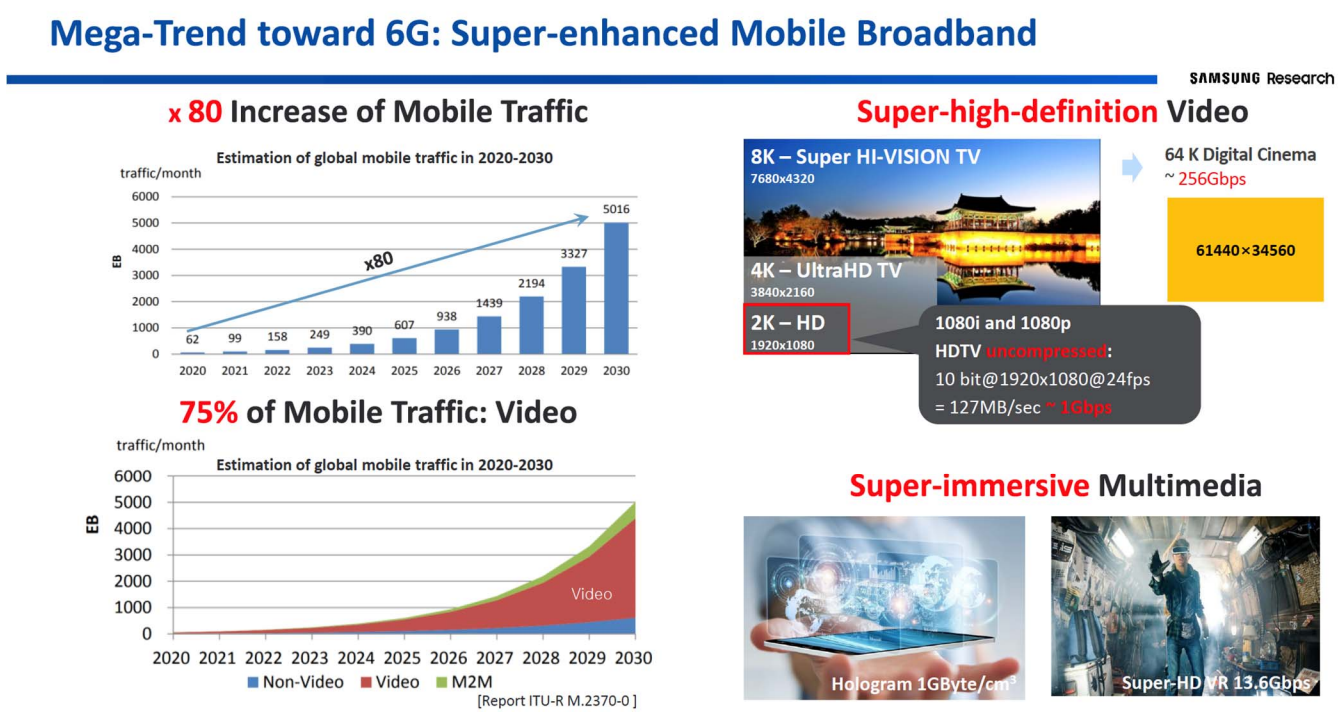


Figure 6-3. Mega-Trend toward 6G: Super-Enhanced Mobile Broadband by 2030. (Samsung[32])

Figure 6-4. Mega-Trend toward 6G: Enhanced Latency, Positioning and Connectivity (Samsung[32])

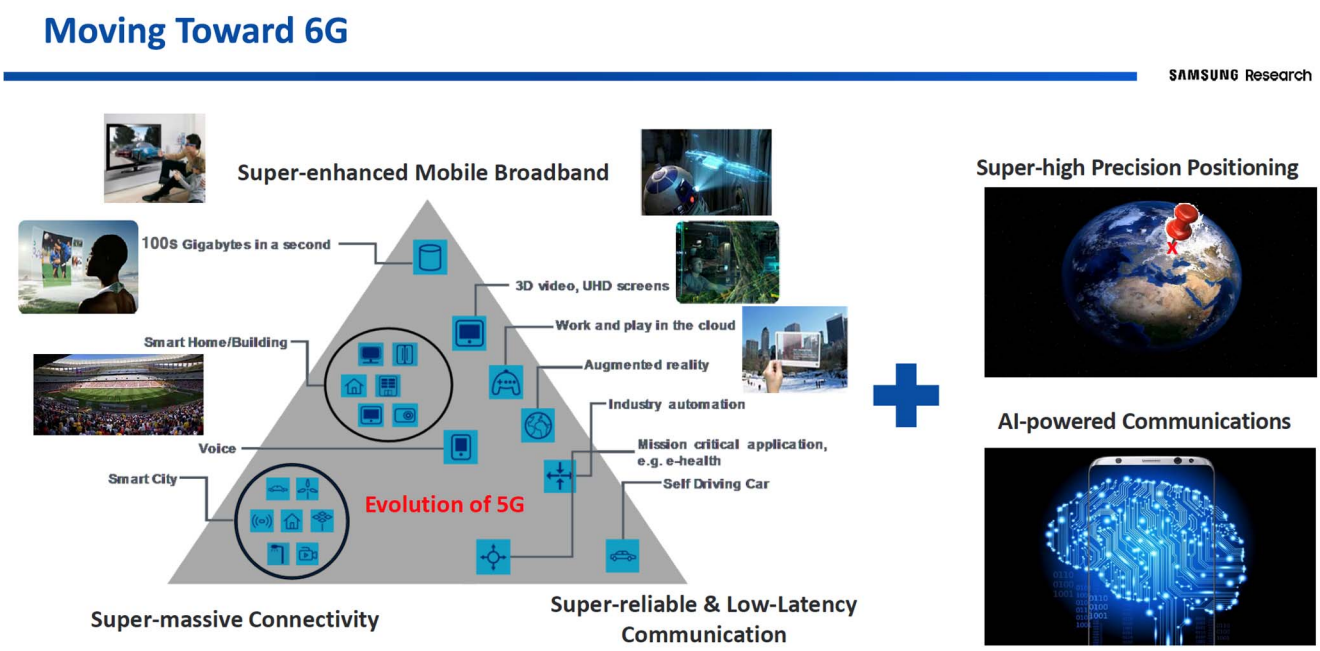


Figure 6-5. "Super-Enhanced" eMBB, M2M and URLLC together with Precision Positioning and AI-powered Communications will be the 6G Core Services by 2030. (Samsung[32])

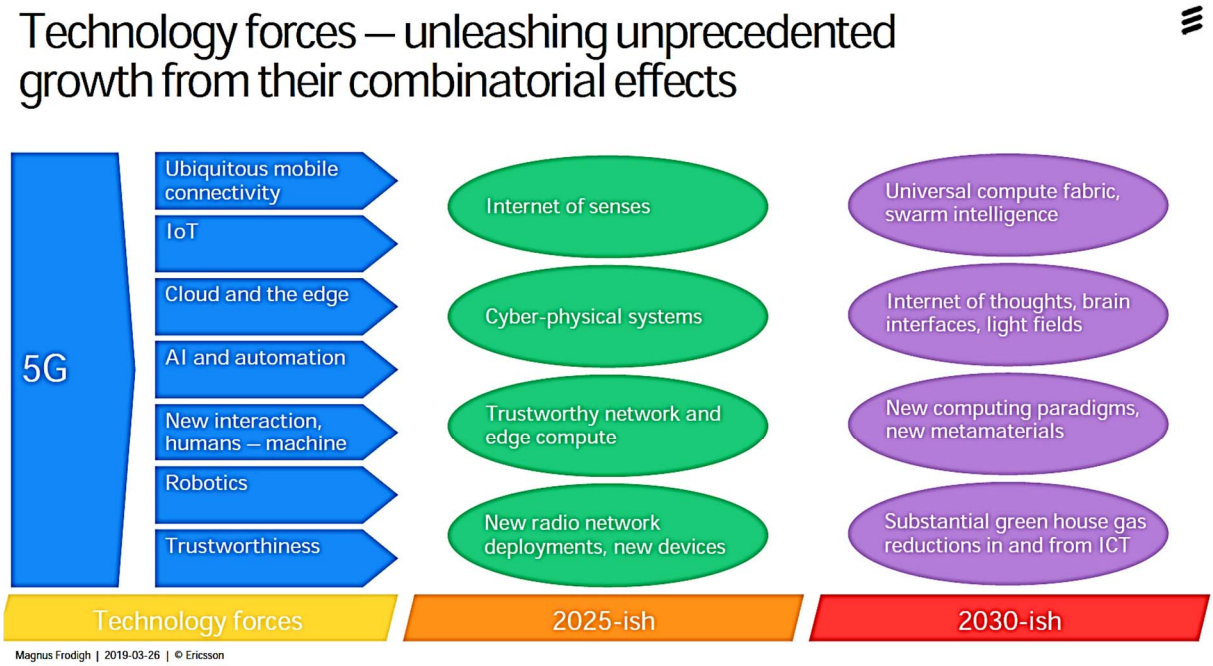


Figure 6.6 From 5G to Beyond 5G Services (Ericsson[40])

The City of Oulu, Finland has vision for 5G & 6G for 2030:[41]

> "Our society is data-driven, enabled by near-instant, unlimited wireless connectivity. 6G will emerge around 2030 to satisfy the expectations not met with 5G, as well as the new ones fusing AI-inspired applications in every field of society with ubiquitous wireless connectivity."

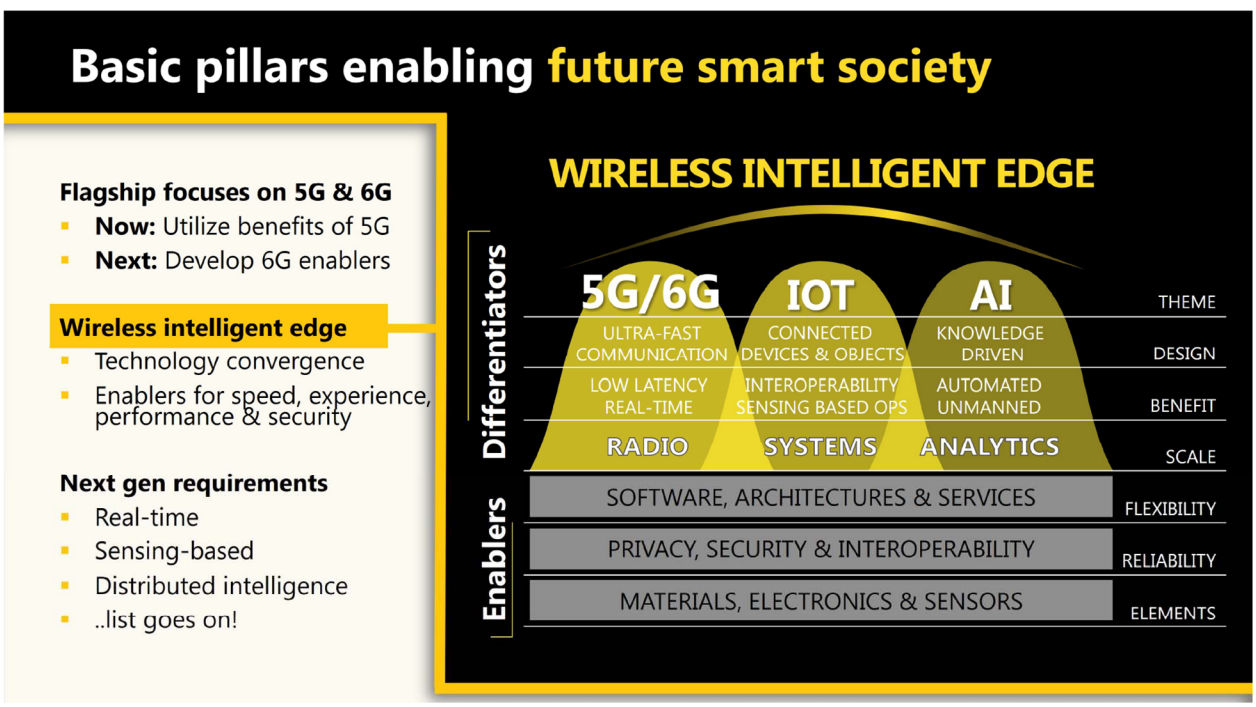


Figure 6-7. Basic Pillars Enabling Future Smart Society (OULU)

[40] Magnus Frodigh, "Towards a connected intelligent future," IEEE 6G Summit 2019, https://www.6gsummit

[41] Juha Ala-Mursula, "5G and beyond from City of Oulu point of view," IEEE 6G Summit 2019, https://www.6gsummit

6.2 Technologies for 5G and Beyond

3GPP Release 16 Plenary level study on NR beyond 52.6 GHz (up to 114.25 GHz) is to be completed during 2019. It is expected to lead study items and work items in the following Releases (years 2020-2022). Studies are now being performed to address high millimeter-wave band requirements. For example, link level performance between 28 GHz (NR Rel'15) and 73 GHz carriers (NR beyond 52.6 GHz) is compared by assuming constant antenna aperture and constant number of antenna elements. Such a study performed by Nokia indicates that 73 GHz band NR could outperform ones at 28 GHz.

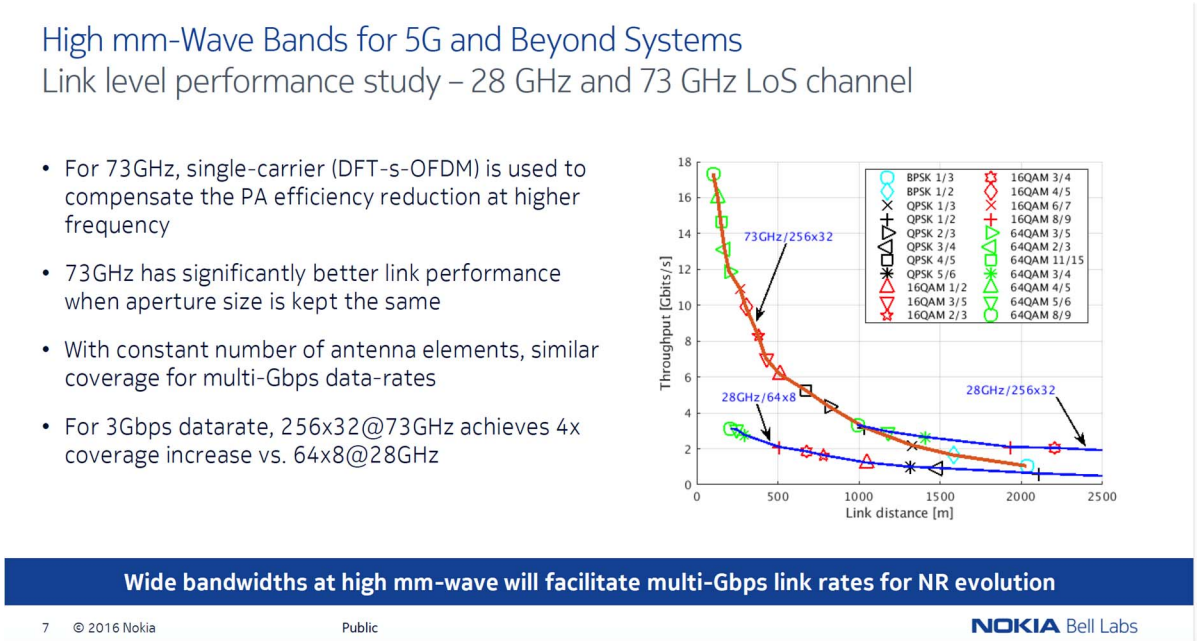


Figure 6-8. Link Level Performance Study between 28 GHz and 73 GHz LoS Channel (Nokia[42])

NR operation on high mm-wave bands requires new technology components because systems have to cope with wider bandwidths, increased path loss, larger arrays and less efficient RF components. However, instead of 64QAM or 256QAM modulation to maximize the throughput with just 400 MHz bandwidth, a 73-GHz radio may have up to 2 GHz bandwidth. This allows the use of lower PAPR modulation schemes like 16QAM. Secondly, given the same physical space in the UE or BS, RFICs with large numbers of antenna elements will be needed.

7.0 Summary

The 5G landscape is in a fast-moving status – a global competition that will set the course of mobile telecommunications for decades to come:

- 4G LTE Today
- 5G 2020's
- 6G 2030's

5G innovations will be needed at all network levels, from physical layer and network layer through applications to support the verticals. 5G microwave and mm-wave hardware will require tight integration between ICs and antenna. Advanced packaging techniques such as 2.5D/3D heterogeneous integration will be critical to the successful development, deployment and advancement of 5G, 6G and beyond. Antenna-in-Package will play a major role for RF Front-End Modules that operate up to 60 GHz. Above 60 GHz, Antenna-on-Chip will become an attractive method for hardware integration.

8.0 HIR 5G TWG Team

Co-chairs: Tim Lee and Herbert Bennett

Members: Harrison Chang, Kamal Samanta, Alberto Valdes-Garcia

Edited by Paul Wesling

[42] Jari Hulkkonen, "High mmWave Bands for 5G and Beyond Systems," IEEE 6G Summit 2019, https://www.6gsummit