

Enabling 5G and Beyond



**International Network
Generations Roadmap (INGR)
Virtual Workshop
Millimeter-Waves and
Signal Process TWG**

Tim Lee
Harish Krishnaswamy
22 October 2020

MMW-SP 10-year Vision

- The use of millimeter-waves is a key enabler to address the ever-increasing demand for bandwidth to transfer Gbps of data across the mobile network to support revolutionary enhancements beyond 4G LTE to impact the quality of life for all humanity.
- If successful, millimeter-wave 5G systems will support and enable new use case scenarios that include computing, Industry 4.0, manufacturing, automotive, healthcare, entertainment, retail and smart cities
- The implications of millimeter-wave spectrum include shared license access possible to reduce cost, and cognitive radio for shared spectrum with satellite or radar. However, there are different propagation models and new architectures for directional and adaptive beam steering to realize solutions to overcome attenuation, blockage, and high-power consumption.
- Over the next 3 to 5 years, the initial deployments of 5G hardware will, at first, grow rapidly for mid-band and more slowly in high-band (millimeter-wave). Within 5 to 10 years, there will be more high-band deployments as the cost of millimeter-wave infrastructure comes down. Within a decade, the attention will turn towards defining 6G with potential use of high millimeter-wave bands (70- to 300-GHz) for another 10X improvements in data rates with low latency

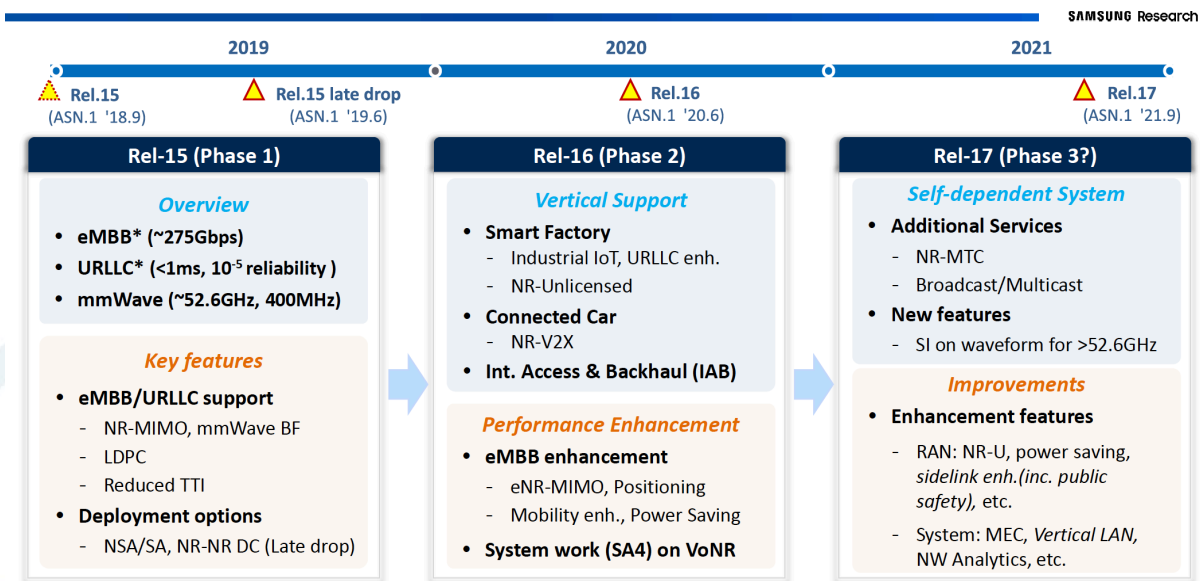
Scope for Millimeter-Waves and Signal Processing Technical Working Group

- Our scope is to identify the challenges and suggest research areas in millimeter-wave architectures, hardware capabilities and signal processing techniques to enable the wide adoption of 5G systems
- Figures of Merit that are useful for hardware implementations for massive mobile broadband (eMBB), ultra-reliable low-latency communication (URLLC) and massive machine to machine (MM2M) use cases will be defined as targets for research within the 3-, 5- and 10-year timeframes
- First edition focused on differences between 4G LTE and 5G, frequency bands, propagation models, semi-conductor technologies, mm-wave RF Front-Ends and heterogenous integration
- Second edition will focus on differentiated needs for Base-Stations and UE and fill in the gaps for cross-TWG collaborations
- What is still missing to be addressed – Support for Satcom and optical back-haul as compared to mm-wave back-haul

Today's Landscape

- 5G system timeline follows the 3GPP releases for 5G NR
- MM-SP TWG will track the mm-waves 5G Standards

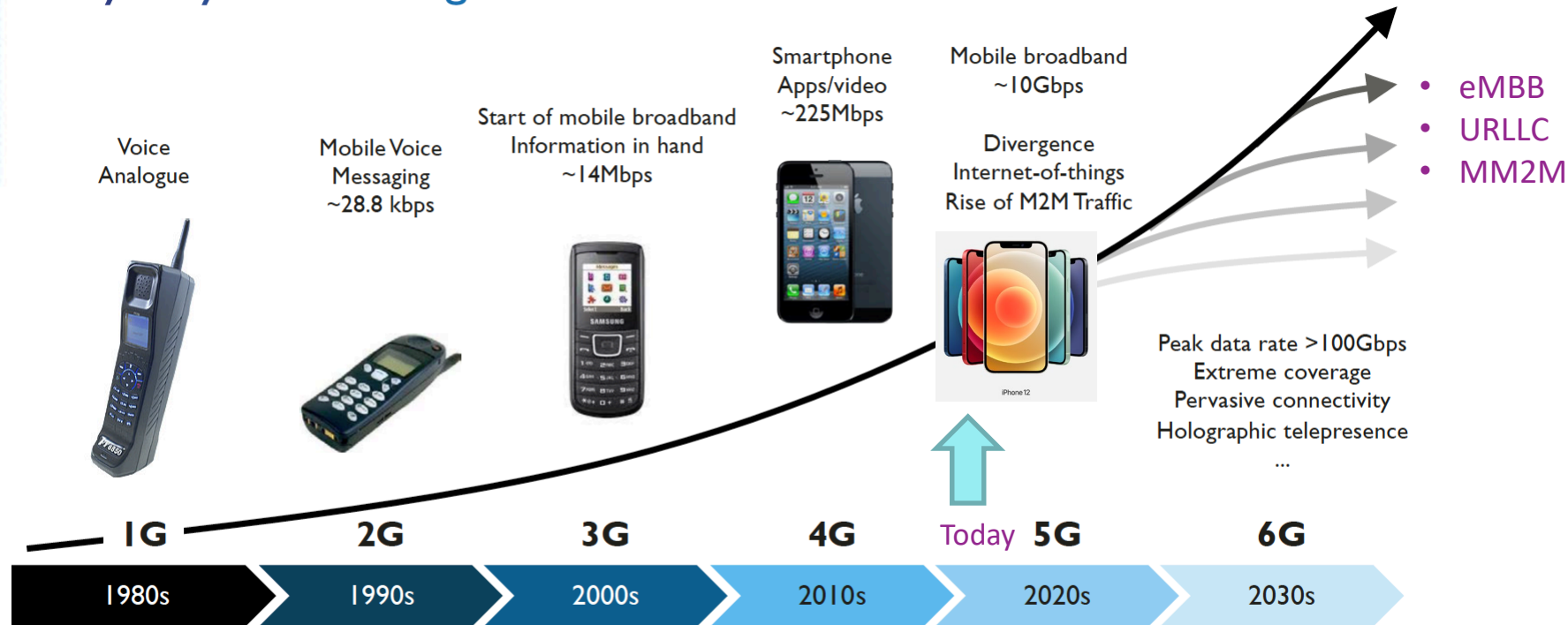
Evolution of 5G Standards in 3GPP



Top Needs for 10-year Vision

- Affordable mm-wave solutions to meet small-cell deployments in urban and rural zones
- Energy-efficient hardware to support operating expenses and green energy objectives
- Dynamic Spectrum sharing to optimize the use scarce spectrum resources
- Inter-operability between legacy 4G LTE, WiFi 6 and satellite networks
- Scalable and customizable implementations to meet or exceed 3GPP specifications for bandwidth, number of users, latency metrics
- Transition from 5G to 6G
- Useful for under-served communities to meet UN Sustainable Development Goals (SDGs)

Every 10 years a new generation of mobile communication



The Landscape of 5G



10x

Decrease in latency:
Delivering latency as low as 1 ms.



10x

Connection density:
Enabling more efficient signaling
for IoT connectivity.



10x

Experienced throughput:
Bringing more uniform, multi-Gbps
peak rates.



3x

Spectrum efficiency:
Achieving even more bits per Hz with
advanced antenna techniques.



100x

Traffic capacity:
Driving network hyper-densification
with more small cells everywhere.



100x

Network efficiency:
Optimizing network energy consumption
with more efficient processing.

Low Band: < 1 GHz, 100Mbps, Mid Band: 1-6 GHz, 1Gbps, High Band: 24-100 GHz, 10 Gbps

<https://www.digitaltrends.com/mobile/5g-vs-lte/>

Manufacturing



Automotive



Computing



Healthcare



Energy



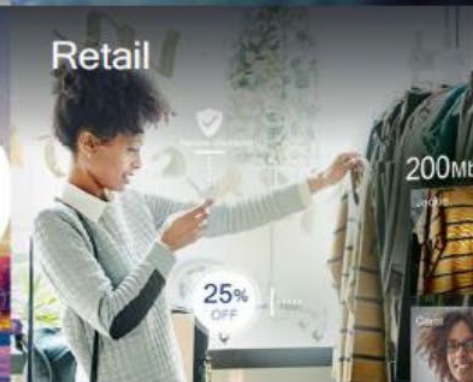
Industrial



Smart cities









Retail



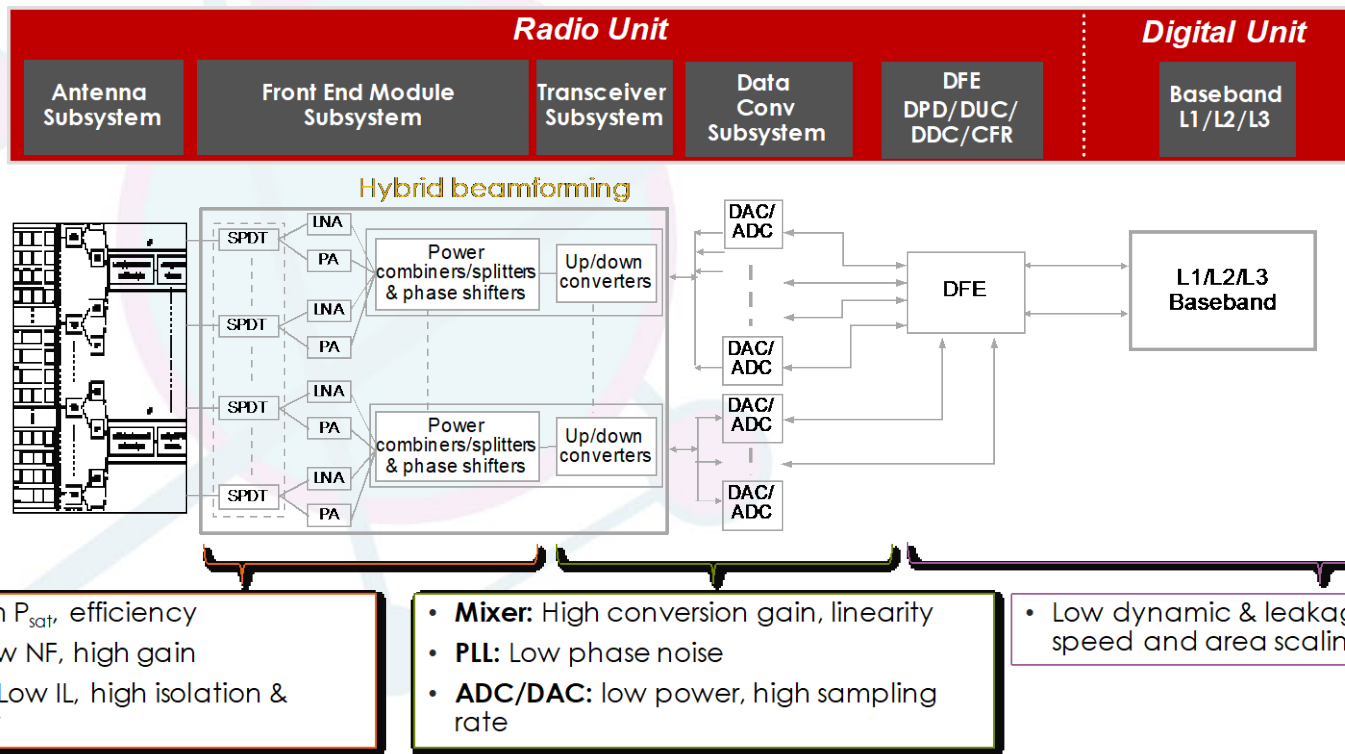
Driving transformation across industries

5G and distributed AI will provide a platform for future innovation

Examples of Use Case Evolution and Network Technologies

	Current services	On the road to 5G	5G experiences
 Enhanced mobile broadband	Browsing, social media, music, video	Fixed Wireless Access, interactive live concerts and sport events	4K/8K videos, mobile AR/VR gaming, immersive media
 Automotive	Wi-Fi hotspots, on-demand GPS map data	Predictive vehicle maintenance, capturing real-time sensor data for different services	Autonomous vehicle control, cooperative collision avoidance, vulnerable road user discovery
 Manufacturing	Connected goods, intra-inter enterprise communication	Process automation and flow management, remote supervision and control of machines and materials	Remote control of robots, augmented reality support in training, maintenance, construction, repair
 Energy and utilities	Smart metering, dynamic and bidirectional grid	Distributed energy resource management, distribution automation	Control of edge-of-grid generation, virtual power plant, real-time load balancing
 Healthcare	Remote patient monitoring, connected ambulance, electronic health records	Telesurgery, augmented reality aiding medical treatment	Precision medicine, remote robotic surgery
 Network technologies	<ul style="list-style-type: none"> > Multi-standard network > Cat-M1/NB-IoT > Cloud optimized network functions > VNF orchestration 	<ul style="list-style-type: none"> > Gigabit LTE > Massive MIMO > Network slicing > Dynamic service orchestration > Predictive analytics 	<ul style="list-style-type: none"> > New Radio (NR) > Virtualized RAN > Federated network slicing > Distributed cloud > Real-time machine learning/AI

Typical mmWave (Infrastructure) Architecture



courtesy Global Foundries

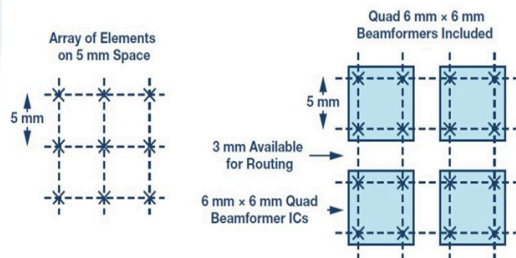
Technology/Capability Challenges & Solutions

Guiding questions:

- What MUST be resolved for evolution to future technologies. Identify gaps in technology sectors (infrastructure, equipment, materials, policy, research)
 - High performance low-cost 5G modems for UE which supports multiple 5G bands
 - Tight Integration for mm-wave Phased Arrays
 - Selection of Semiconductor Technology Based on Output Level
- Core competencies that are disconnected or missing?
 - Multi-physics based design tools that enable optimization of electrical, mechanical, analog, digital and antenna functions
 - Low-Loss substrates with fine-pitch geometries
- Who are the key players? (Industry sectors? Types of research needed?)
 - Silicon and GaAs/GaN foundries
 - OSAT – for advanced packaging technology

Technology/Capability Gaps and Showstoppers

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

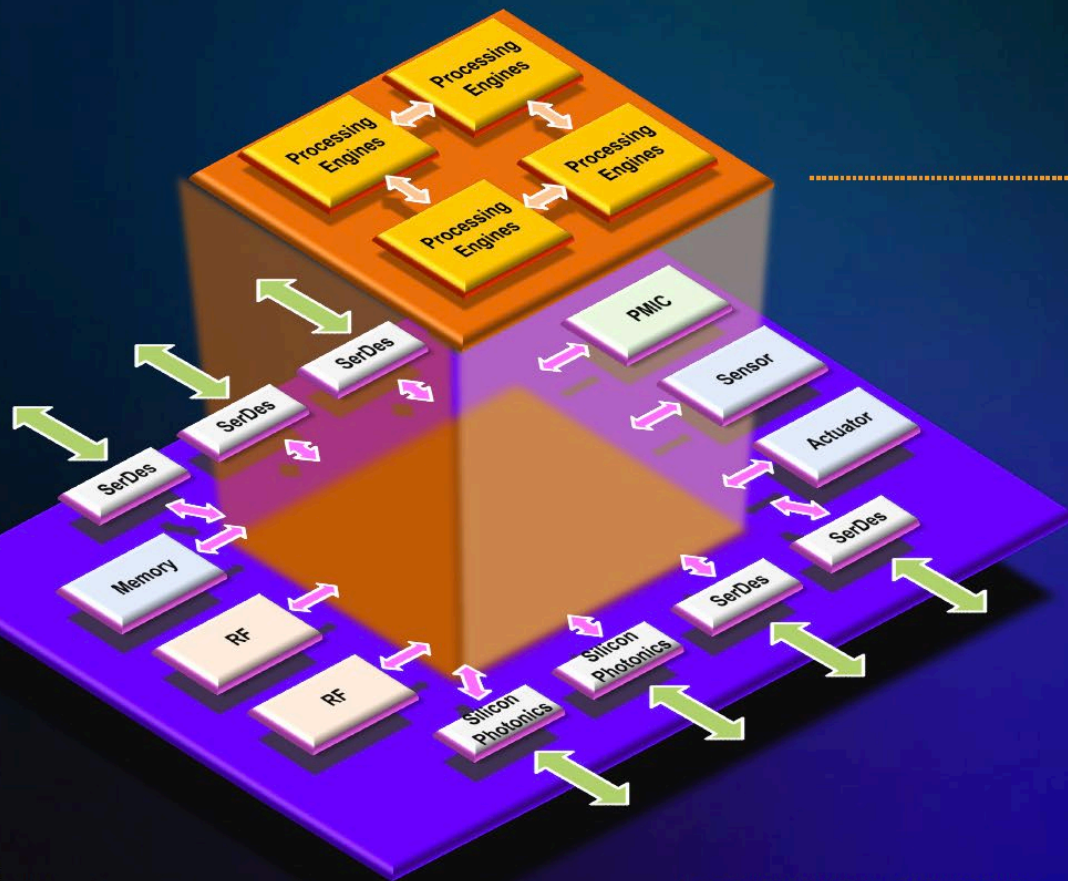


- ▶ At 30 GHz, $\lambda/2 = 200$ mils, or 5 mm
- ▶ Electronics Footprint a Serious Challenge
 - Worse for Dual Pole
- ▶ Front-End Function Desired in Beamformer Package
 - PAs and LNAs

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

Chiplet : More than Moore

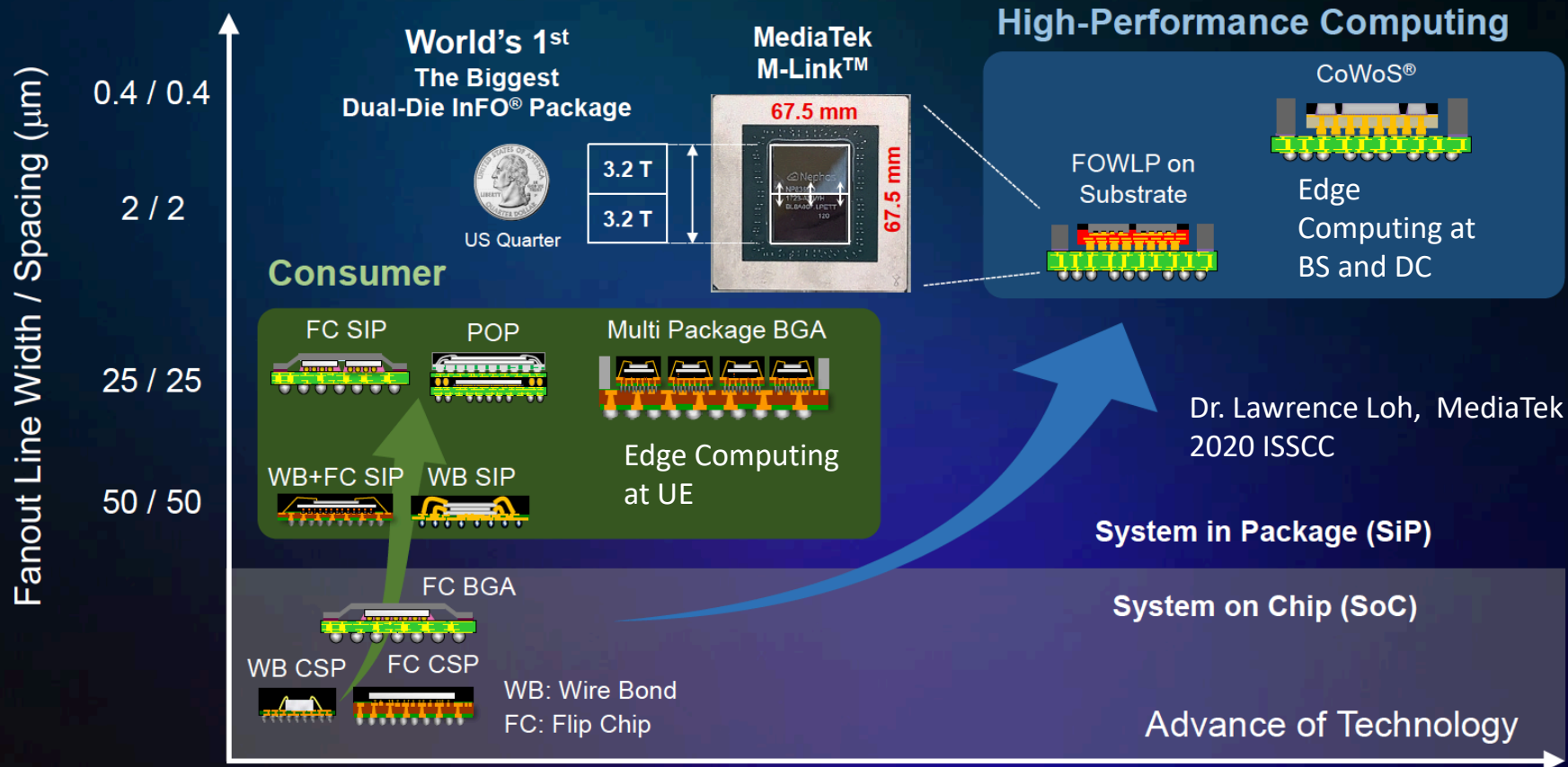


**Homogeneous
Integration**

**Heterogeneous
Integration**

Interconnect

Advances of Package for Chiplet Integration



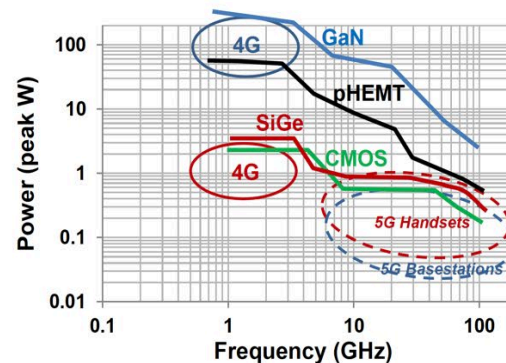
Technology/Capability Gaps and Showstoppers

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

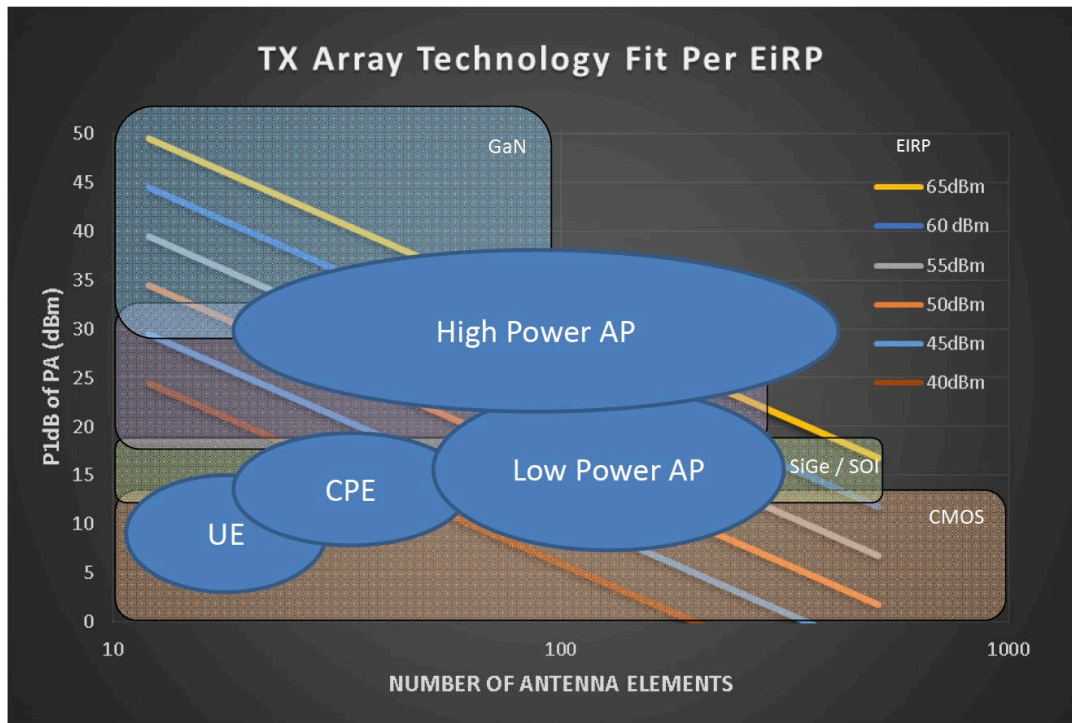
Estimated Power Ranges for 5G TX ICs & Estimated Max Power of Different Technologies



Technology Fit Per Radio Form Factor

- UE is clearly in CMOS technology domain
- CPE spans CMOS and SiGe BiCMOS
- Low power access point spans CMOS, SiGe BiCMOS and GaAs
- High power access point spans GaAs and GaN

5G Roadmap will address the system trade between Silicon and III-V



Overall Potential Solutions – for those Gaps that need solutions by a certain timeframe

- What Other Areas of opportunity? KEY QUESTION: What must happen to enable a solution?
 - Known solutions – mmWave and beamforming technologies from radar and SATCOM
 - Challenged solutions – why are these a challenge?
 - mmWave RF Front-Ends at scale (millions of units)
 - Fitting even more bands into the FEM with Advanced Packaging
 - Design for Test
 - Unknown solutions – identify gaps in knowledge
 - Accurate channel and propagation models for mmWaves (outdoors, indoors, urban, rural)
 - mmWaves signals will not penetrate buildings

Active Circuits Needs, Challenges and Potential Solutions

Need Challenge(s) and Enablers and Potential Solutions Sets	Current State (2019) (details)	3 years (2022) (details)	5 years (2024) (details)	Future State 10-years (2029) (details)
Need: Active Components – LNA, PA, PS, Switches, Mixers	silicon RFIC + GaAs/GaN PA and SW	all silicon – analog beamformer	all silicon – analog, digital and hybrid beamformers (20 GHz to 40 GHz)	all silicon - digital beamformers (20 GHz to 40 GHz, 60 GHz, 80 to 120 GHz)
Challenge(s) for Need	High parts count/complexity to support > 40 band	Even higher complexity to add sub-6GHz and mm-waves bands	ADC/DAC data converter at every element for EDBF, Multiple RAT for each mm-wave band	Programable RAT that can generate waveforms for multiple use cases, extremely wideband components
Possible Solution for Challenge	non-beamformer – PS not needed	Antenna in Package (AiP) integration (2.5D)	Antenna in Chip (AiC) integration (2.5D), leverage antenna gain	3D-stacked RFFE vertical integration; wafer level integration

Advanced Thin-Profile Fan-Out with Beamforming Verification for 5G Wideband Antenna

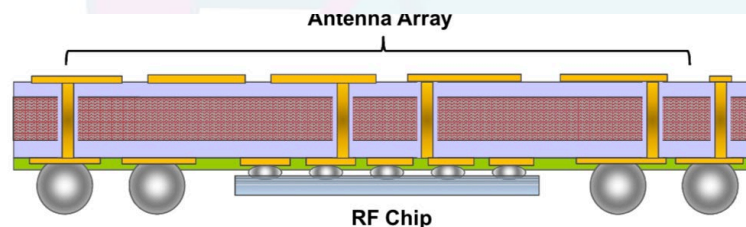


Fig.3. Cross-section view of the mmWave transceiver on flip chip ball grid array (FCBGA) AiP.

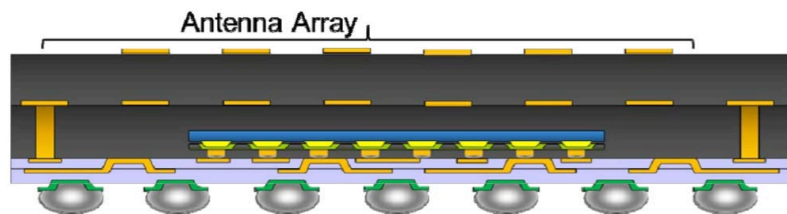
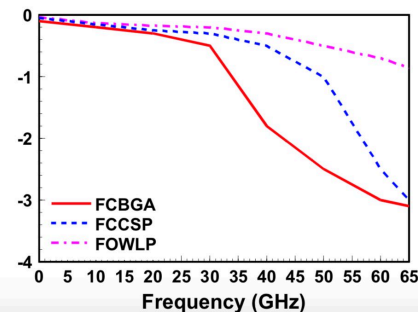
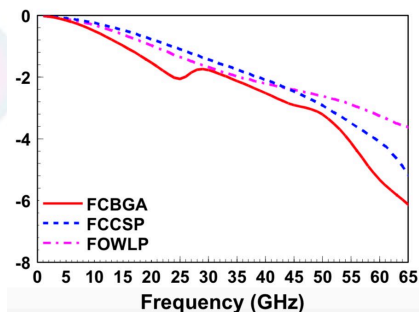
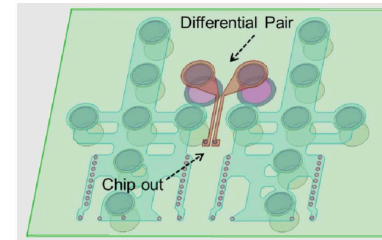
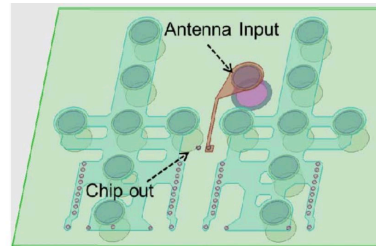


Fig. 8. Geometry of the fan-out Antenna in Package



Sheng-Chi Hsieh et al, ECTC2019, ASE

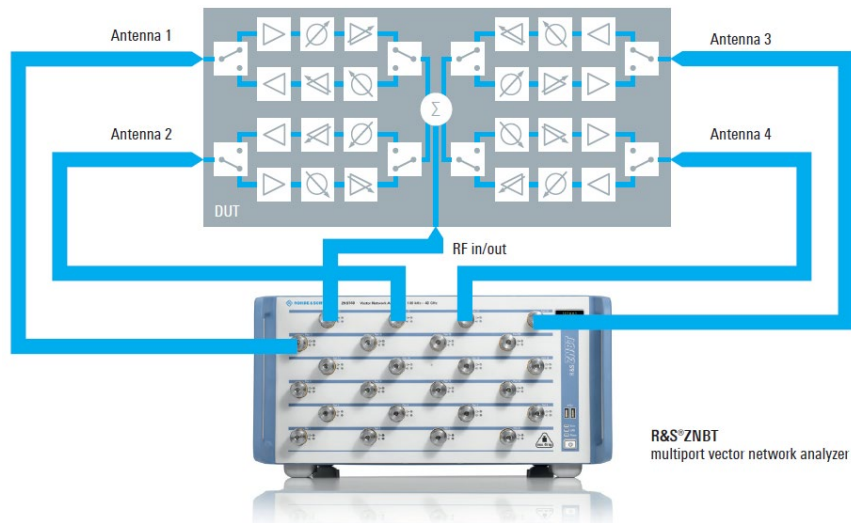
Design for Test Needs, Challenges and Potential Solutions

Need Challenge(s) and Enablers and Potential Solutions Sets	Current State (2019) (details)	3 years (2022) (details)	5 years (2024) (details)	Future State 10-years (2029) (details)
Need: Design for Test	Testing at component, cell and array levels	Low cost mfg. OTA (Over the Air) test up to 60GHz	Low cost mfg. OTA (Over the Air) test up to 120GHz	Low cost mfg. OTA (Over the Air) test up to 400GHz
Challenge(s) for Need	Cost of testing and yield loss	Isolation box, test equipment, known good units	Calibration for unit variation	Testing and calibration of array on chip
Possible Solution for Challenge	mmWave chamber, passive and active measurement Separate design, test and verification environments result in issues discovered at test	Correlated box w/ chamber, standard interface w/ golden unit Integrated design, test and verification environments reduce issues discovered at test	Build-in self calibration on package Multi-physics-based simulators enable co-design of EM, thermal and radiated patterns to enable correct by design at FEM level	Build in self-test and self-calibration on chip with self-repair. Achieve > 95% for FEM at 20 to 40 GHz

Technology/Capability Gaps and Showstoppers

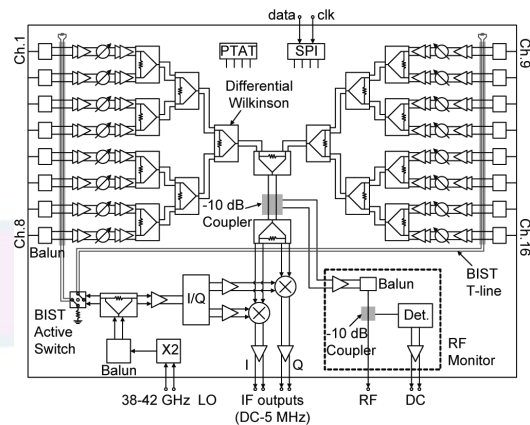
Challenge 3: Low-Cost mmWave Volume Testing

Today: Rack-and-Stack Tester

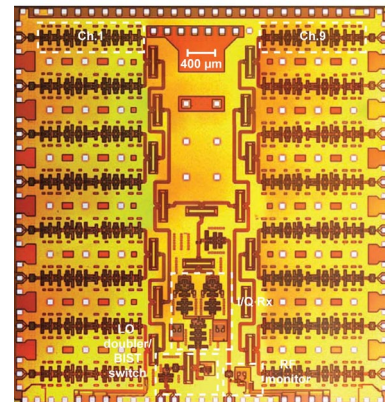


courtesy Rohde and Schwarz

Tomorrow: Built-in-Self-Test on the IC



[S-Y Kim, TMTT 2013]



Visit Our Website | futurenetworks.ieee.org/roadmap

First Gen RFFE Cost Comparison (5G vs LTE)

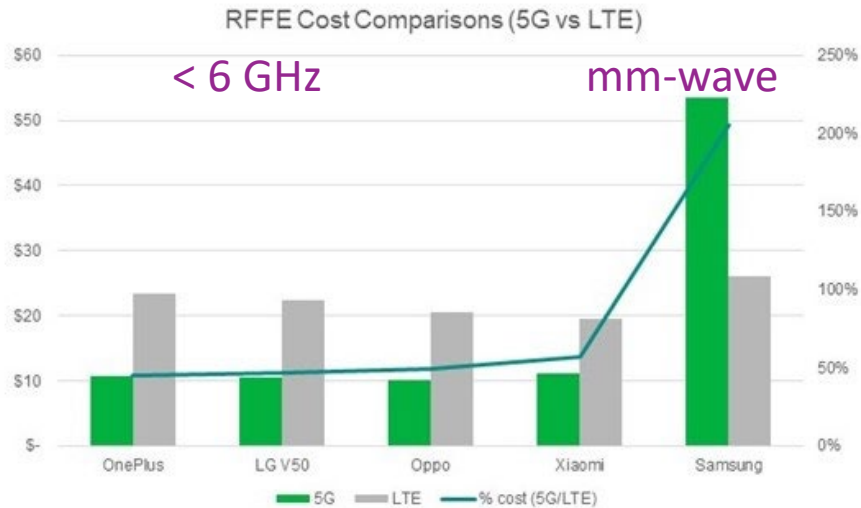


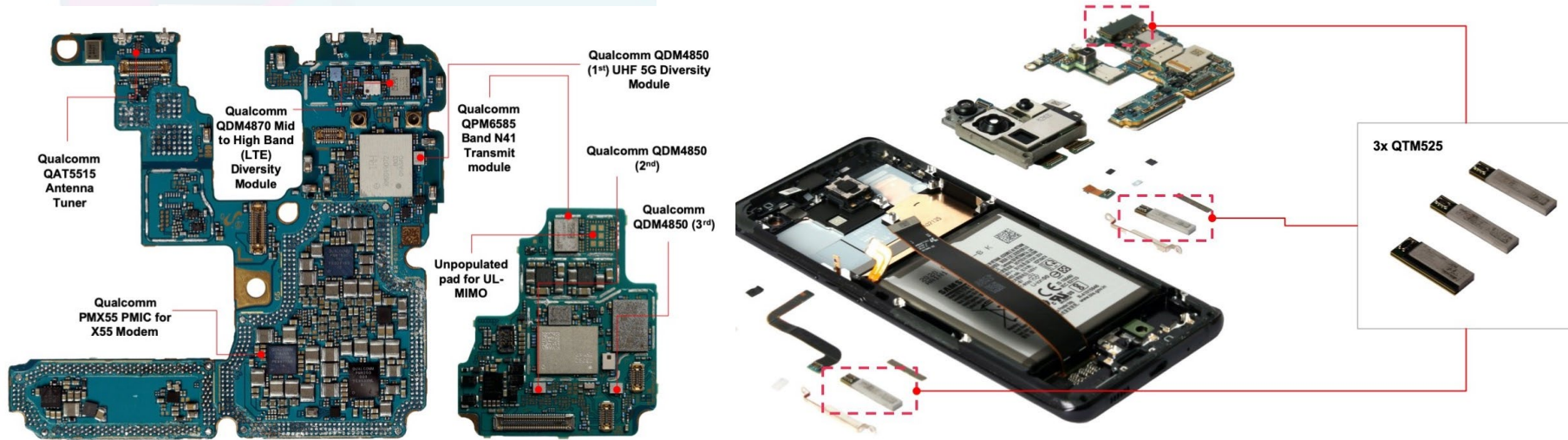
Chart 6 – Component cost comparisons of all 5 Qualcomm 5G designs

- Based on tear-downs, sub-6GHz 5G RFFE carries a cost premium of around half of the cost of existing LTE RFFE.
- While the mmWave solution represent a staggering twice the cost of existing LTE RFFE.
- Subsequent generations of 5G phone design should lessen the 5G RFFE cost premium. In mature 5G designs, the 5G RFFE is expected to be absorbed into an integrated 5G/4G/3G RFFE design.

<https://technology.ihs.com/616863/in-5g-smartphone-designs-rf-front-end-graduates-from-traditional-supporting-role-to-co-star-with-modem>

Samsung S20 Ultra mm-wave 5G Phone

Teardown Photos



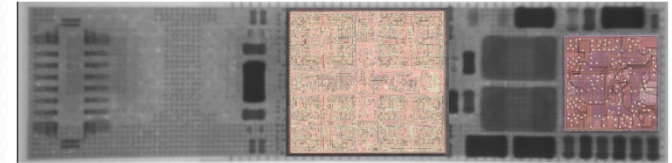
<https://technology.informa.com/623134/5g-modem-to-rf-integration>

First-Gen Samsung S20 Ultra 5G mm-wave SiP

- Qualcomm QTM525 antenna modules within the Samsung contains everything from a phased-array antenna all the way to the RF transceiver.
- High level of integration needed to overcome the nature of mmWave attenuation.
- The entire mmWave RFFE chain has to be shortened to ensure signal integrity within the link budget of the connection.



QTM525 mmWave Antenna



Qualcomm QTM052 mmWave Antenna Module



Height = 1.75 mm

<https://technology.informa.com/623426/5g-rf-front-end-leans-heavily-on-advanced-packaging-for-integrated-rf-modules>

Apple iPhone 12 – X55 5G Modem



iphone 12的主板

<https://www.myfixguide.com/iphone-12-teardown/>



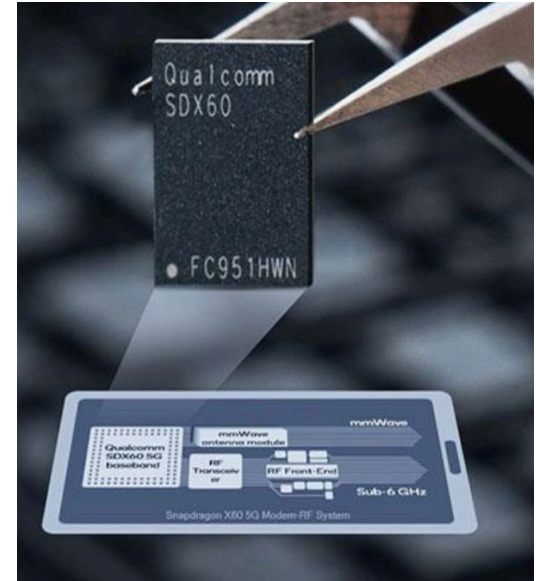
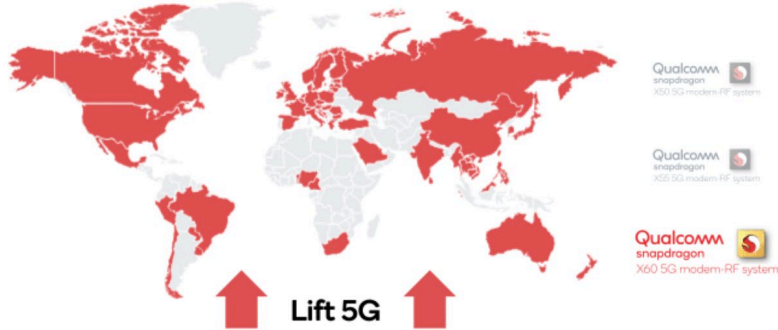
Qualcomm
X55 5G
Modem used
in iPhone 12

Qualcomm X60 5G Modem – Next Gen

- Snapdragon X60 5G Modem-RF System - commercial **modem-to-antenna solution** which includes the baseband, RF transceiver, and complete RF front-end for mmWave and sub-6 GHz.

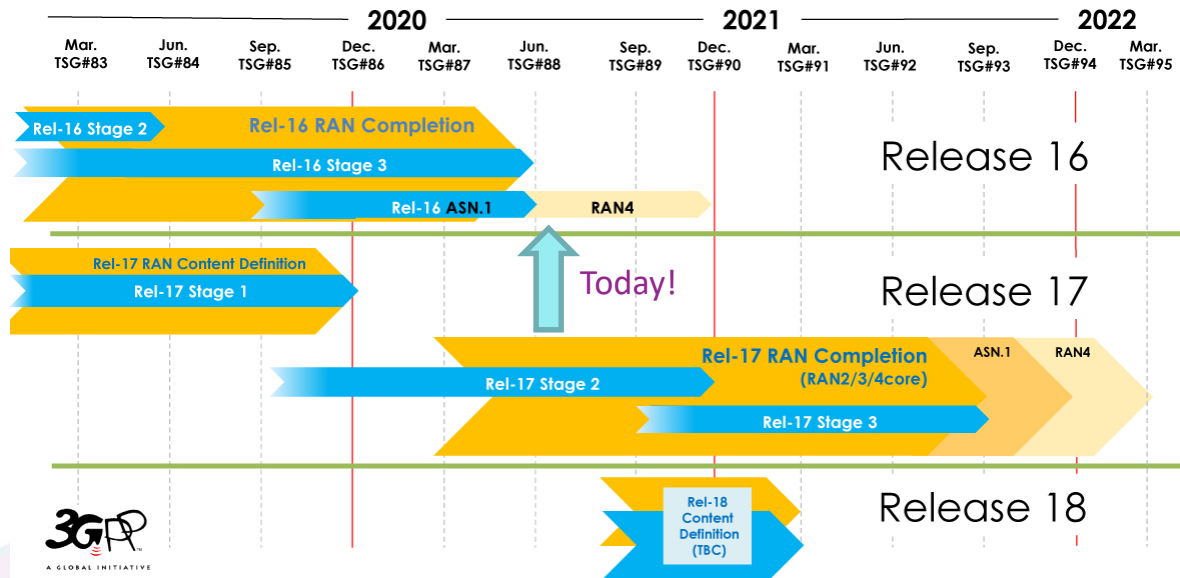
Driving 5G expansion and acceleration

Snapdragon X60 3rd gen 5G solution



<https://www.qualcomm.com/news/onq/2020/02/18/introducing-snapdragon-x60-raising-global-5g-performance-bar-worlds-most>

What's new in 3GPP Release 16?



Source: 3GPP TSG SA#87e, 17-20 March 2020, e-meeting document SP-200222

© 3GPP 2020

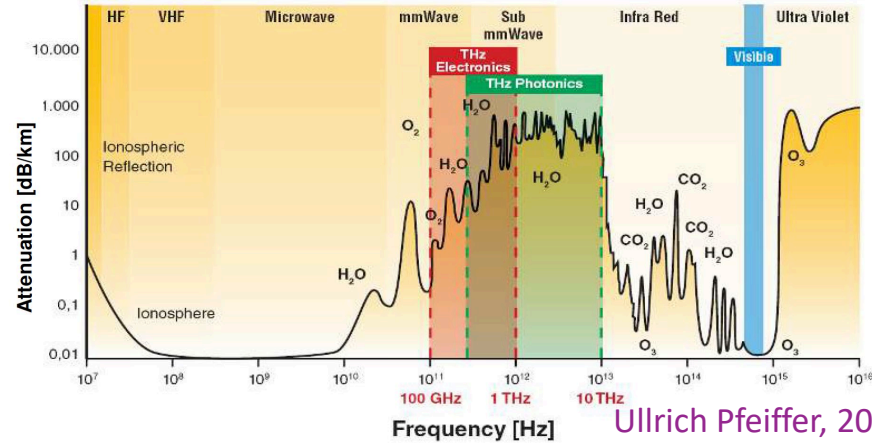
<https://www.3gpp.org/release-16>

Release 16

- The 5G System – Phase 2
- V2x Phase 3: Platooning, extended sensors, automated driving, remote driving
- Industrial IoT
- Ultra-Reliable and Low Latency Communication (URLLC) enh.
- NR-based access to unlicensed spectrum (NR-U)
- 5G Efficiency: Interference Mitigation, SON, eMIMO, Location and positioning, Power Consumption, eDual Connectivity, Device capabilities exchange, Mobility enhancements
- Integrated Access and Backhaul (IAB)
- Enh. Common API Framework for 3GPP Northbound APIs (eCAPIf)
- Satellite Access in 5G
- Mobile Communication System for Railways (FRMCS Phase 2)

How About 6G?

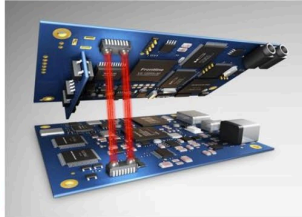
- 5G – 2020 to 2029
- 6G – 2030 to 2040
- Sub-THz frequency band
 - Very large bandwidth
 - High path loss
 - Edge of silicon technologies



Ullrich Pfeiffer, 2019 6G Summit



Kiosk



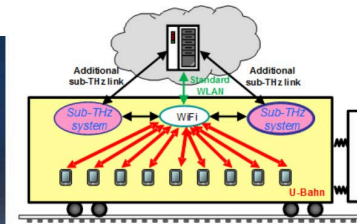
Board to board



Data centers



VR



Backhaul offloading

6G will drive new technical demands in five major areas

- Next-generation radio in all bands plus the addition of bands above 100GHz. Includes new technology to improve spectral and energy efficiency <8GHz, generational improvements in 20-70GHz mmWave, and adding Sub-THz (100-1000 GHz) for communications, sensing, and imaging.
- Integrated heterogeneous multi-radio access technology (RAT) systems - Seamless and intelligent use of 6G radio systems with non-terrestrial networks as well as legacy wireless systems, personal area networks, and near field communication (NFC).
- Time engineering in networks: Further reduce latency, add predictable and programmable latency for precise-time applications.
- AI-based networking: The use of artificial intelligence (AI) to optimize real-time network operations and performance. Also, the connectivity and sharing of pervasively distributed AI data, models, and knowledge.
- Advanced security: Pervasive application of security technology for privacy, attack prevention, attack detection, attack resilience, and recovery in a zero-trust environment.

6G Applications & Semiconductor Technologies

Mm-Waves & THz – The potential for 6G

- Wireless Cognition
 - Robotic Control
- Sensing
 - Air Quality Detection
 - Personal Health Monitoring
 - Gesture Detection
- Imaging
 - mmWave Camera (see in dark)
 - High-Definition radar
 - THz security body Scan
- Communications
 - Wireless fiber backhaul
 - Intra-device radio communications
- Positioning
 - Centimeter-level Positioning

• Objective

- Support high data rate Communications
- Spatial multiplexing for high capacity

• Benefits (140 – 1000 GHz)

- Large available spectrum
- Shorter wavelength – more channels for same sized array

• Challenge

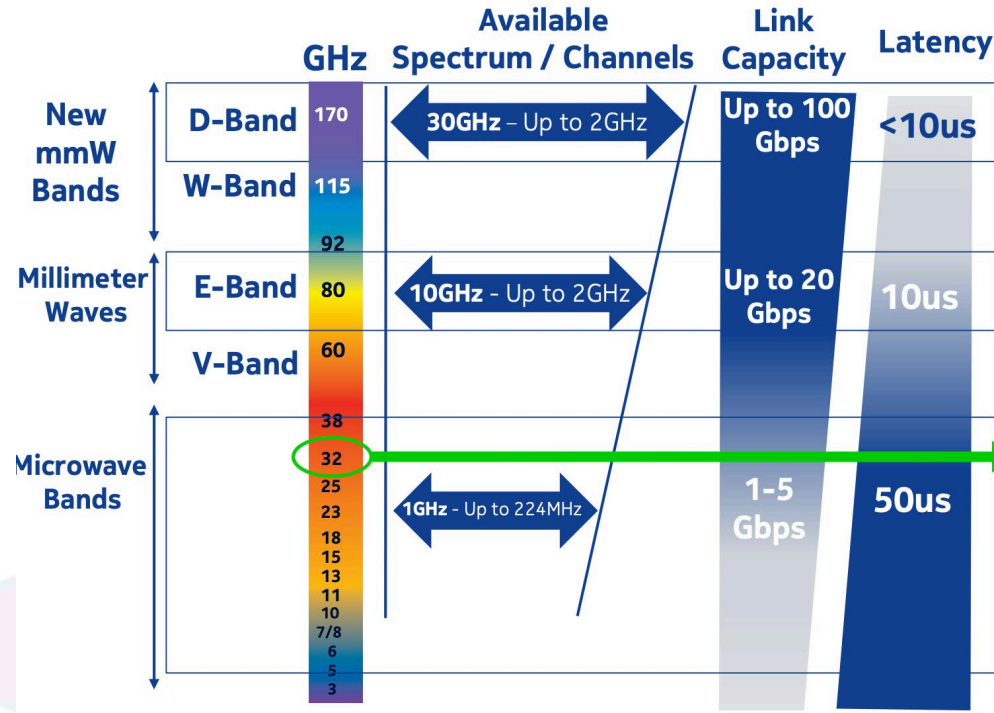
- Atmospheric attenuation
- PAA element spacing - $\sim \lambda/2$ @ 150 GHz is 1 mm
- Challenging packaging technologies

• Technologies

III-V: InP HBT, InP HEMT, GaN HEMT, SiGe

- Heterogeneous Integration
- Small Form Factor
- Antenna On Chip

D-Band Radio on Glass (Nokia Bell Labs)

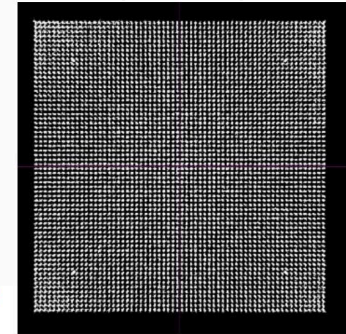


Goal: Highly integrated and cost-effective mm-wave modules with high spectral-efficiency at D-band



NOKIA Wavence
UBT-S

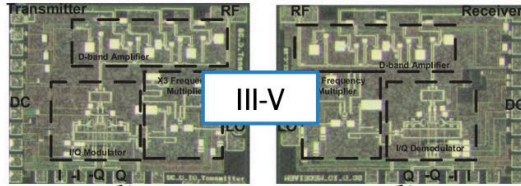
DP - 4096QAM
(24b/s/Hz)



[Baeyens *et. al.*]

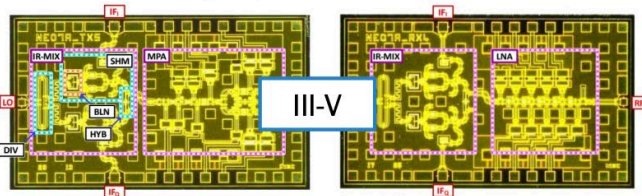
Challenges for Integrated D-band System

IC Technology



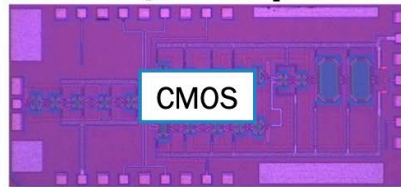
III-V

[Carpenter *et. al.*]



III-V

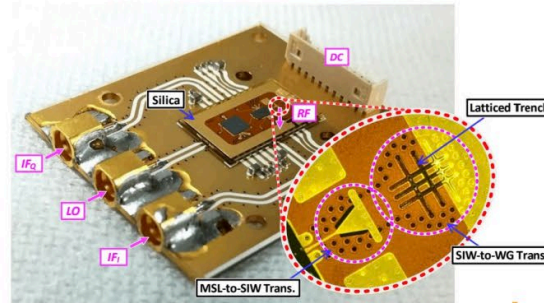
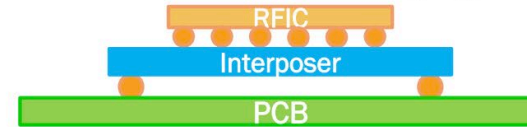
[Ito *et. al.*]



CMOS

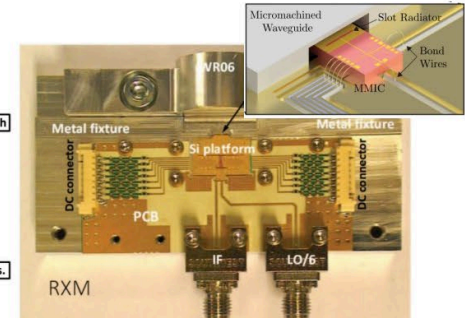
[Mohammadnezhad *et. al.*]

RF Interface & Packaging



[Ito *et. al.*]

- SIW to Waveguide Transition on silica-based substrate
- Loss = 1.75 dB



[Li *et. al.*]

- An on-chip slot radiator mounted in the micromachined waveguide's H-plane
- Loss = 4.4 – 5.5 dB

Design for Multiple Use Case Needs, Challenges and Potential Solutions

Need Challenge(s) and Enablers and Potential Solutions Sets	Current State (2019) (details)	3 years (2022) (details)	5 years (2024) (details)	Future State 10-years (2029) (details)
Need: Design for multiple Use Cases	Point designs customized for single use cases and RATs	Use case switched designs for multiple freq. bands, cell sizes and data rates, manually selected	Programmable configuration DSP and switch fabrics, availability of CPU, memory and data converters	Fully autonomous reconfigurability and upgradability for all major use cases for resiliency, QoS and optimum utilization of resources
Challenge(s) for Need	Complexity, Cost	Complexity, Cost as production volumes rise; building penetration	Reduced complexity through adoption of digital techniques	RAT agnostic architecture, Software Defined Radio Heads
Possible Solution for Challenge		Common & Modular architecture	Optimized RFFE, universal DSP and baseband processor. Chiplets integration extends useful product lifecycle	Standardized interfaces, use of AI/M co-processor or accelerator in RFFE SoC with self-repair

Issues and Topics Expected to be Addressed in 2020 2nd Edition of INGR

- More accurate technology assessment as problems are discovered during initial 5G rollout
- Beginning tracking of Rel 17 architecture, specifications, and gaps
- Design for Multiple Use Cases
- What do **YOU** think?
 - We want your feedback
 - To email us, write to **5GRM-mmWave@ieee.org**

Get involved!

Working Group Members

Antonino Orsino
 Antonino Orsino
 Arthur Giordano
 Arthur Paoella
 Ashutosh Dutta
 Brad Kloza
 Doriana Guiducci
 Dr Xiang Gui
Harish Krishnaswamy
Harrison Chang
 Huan-Yang Chen
 Jeongho Park
 John Cioffi
 Linda Wilson
 Marcel Wieland
 Matti Latva-aho
 Michele Polese
 Mike Garner
 Navin Kumar
 Noureddine Hamdi
 Puneet Mishra
 Shahzada Rasool
Steven Platt
 Sumit Roy
 Theresa Cavrak
Timothy Lee
 Youssef Nasser
Anding Zhu
Alberto Valdez Garcia

antonino.orsino@ericsson.com
 antonino.orsino@TUT.FI
 agior@VERIZON.NET
 apaolell@HARRIS.COM
 ad37@CAA.COLUMBIA.EDU
 b.kloza@ieee.org
 Doriana.Guiducci@eco.cept.org
 X.Gui@MASSEY.AC.NZ
 hk2532@COLUMBIA.EDU
Harrison_Chang@ASEGLOBAL.COM
 ctnm83@ZEBRA.COM
 jeongho.jh.park@SAMSUNG.COM
 cioffi@STANFORD.EDU
 linda_wilson1225@IEEE.ORG
 wieland.marcel@GLOBALFOUNDRIES.COM
 matti.latva-aho@OULU.FI
 michele.polese@GMAIL.COM
 mike.c.garner@att.net
 navinkumar@IEEE.ORG
 noureddine.hamdi@GMAIL.COM
 mishra_puneet@IEEE.ORG
 Shahzada.Rasool@sprint.com
steven@ieee.org
 sroy@UW.EDU
 t.cavrak@ieee.org
tt.lee@IEEE.ORG
 youssef.nasser@ieee.org

For additional information, contact the
 mmWave WG Co-Chairs

Timothy Lee - tt.lee@ieee.org

Harish Krishnaswamy hk2532@columbia.edu

If you would like to join the working group
 please send mail to:

5GRM-mmWave@ieee.org



QUESTIONS?