IEEE Future Networks

Enabling 5G and Beyond

International Network Generations Roadmap (INGR)

Virtual Workshop

Millimeter-Waves and Signal Process TWG

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IEEE

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

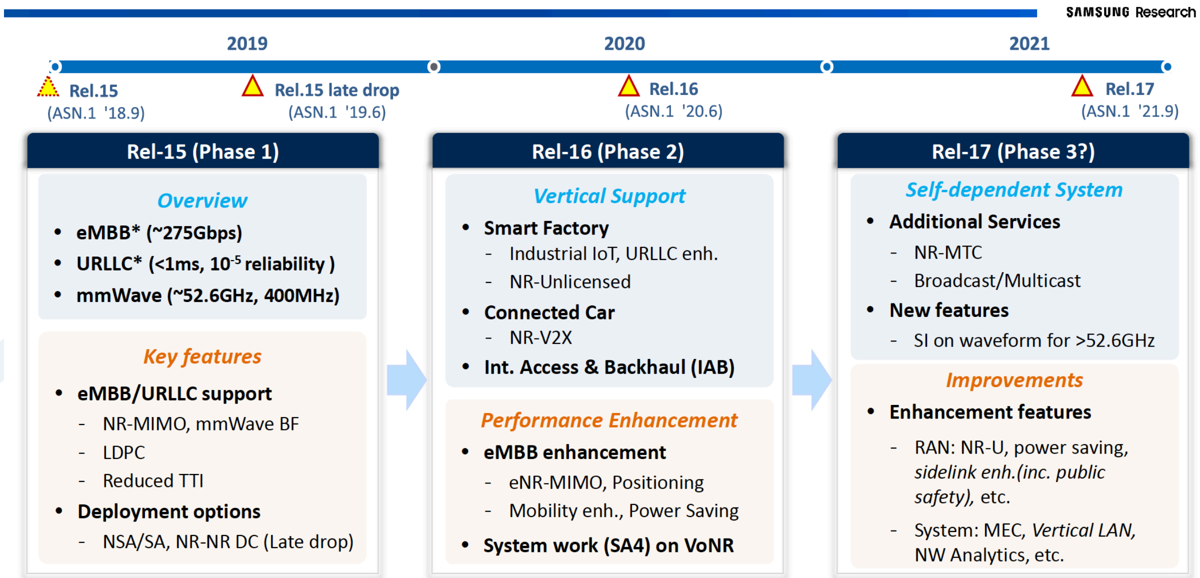
Scope for Millimeter-Waves and Signal Processing Technical Working Group

- 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 to 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

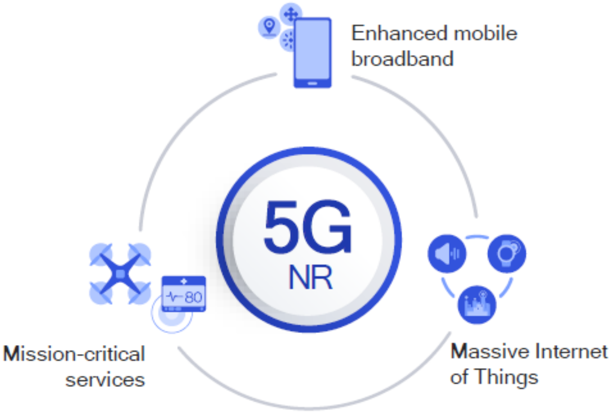
- Affordable mm-wave solutions to meet small-cell deployments in urban and rural zones
- Energy-efficient hardware to support operating expenses and green energy objectives
- Dynamic Spectrum sharing to optimize the use scarce spectrum resources
- Inter-operability between legacy 4G LTE, WiFi 6 and satellite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

Driving transformation across industries

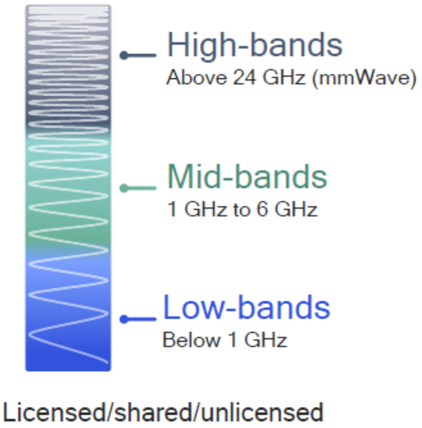
5G and distributed AI will provide a platform for future innovation

Source: Qualcomm 2019

Designing a unified, more capable 5G air interface



Diverse services

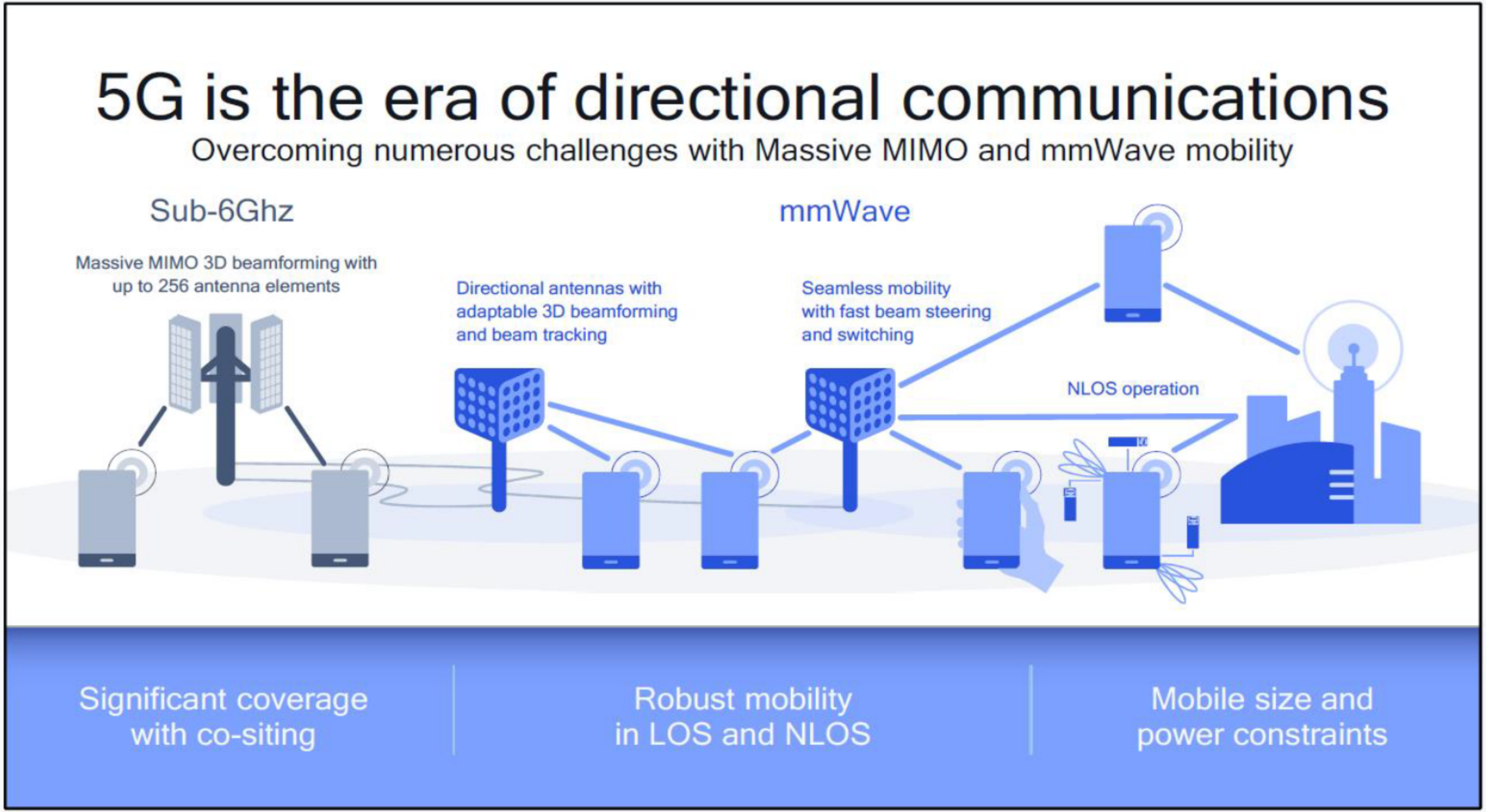


Diverse spectrum

Diverse deployments

Courtesy: Qualcomm: Making 5G NR a Commercial Reality, Sept 2018

Existing, emerging, and unforeseen services - a platform for future innovation



Source: Qualcomm 2019

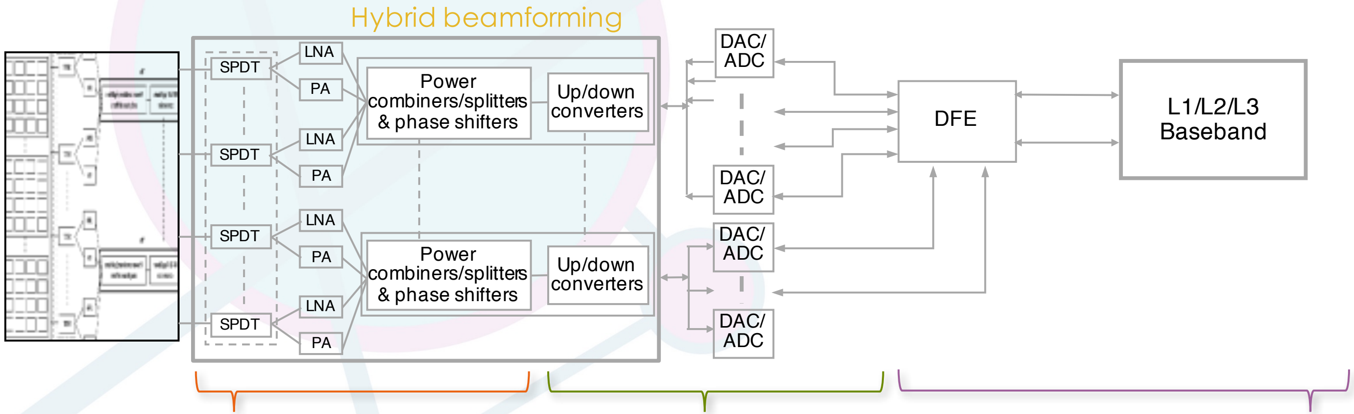
Typical mmWave (Infrastructure) Architecture

Radio Unit

Antenna Subsystem | **Front End Module Subsystem** | **Transceiver Subsystem** | **Data Conv Subsystem** | **DFE DPD/DUC/ DDC/CFR**

Digital Unit

Baseband L1/L2/L3



- **PA:** High P_{sat}, efficiency
- **LNA:** Low NF, high gain
- **Switch:** Low IL, high isolation & linearity

- **Mixer:** High conversion gain, linearity
- **PLL:** Low phase noise
- **ADC/DAC:** low power, high sampling rate

- Low dynamic & leakage power, high speed and area scaling

courtesy Global Foundries

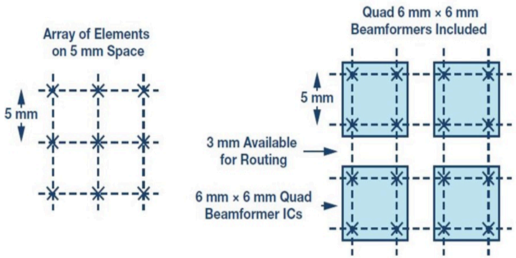
Technology/Capability Challenges & Solutions

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

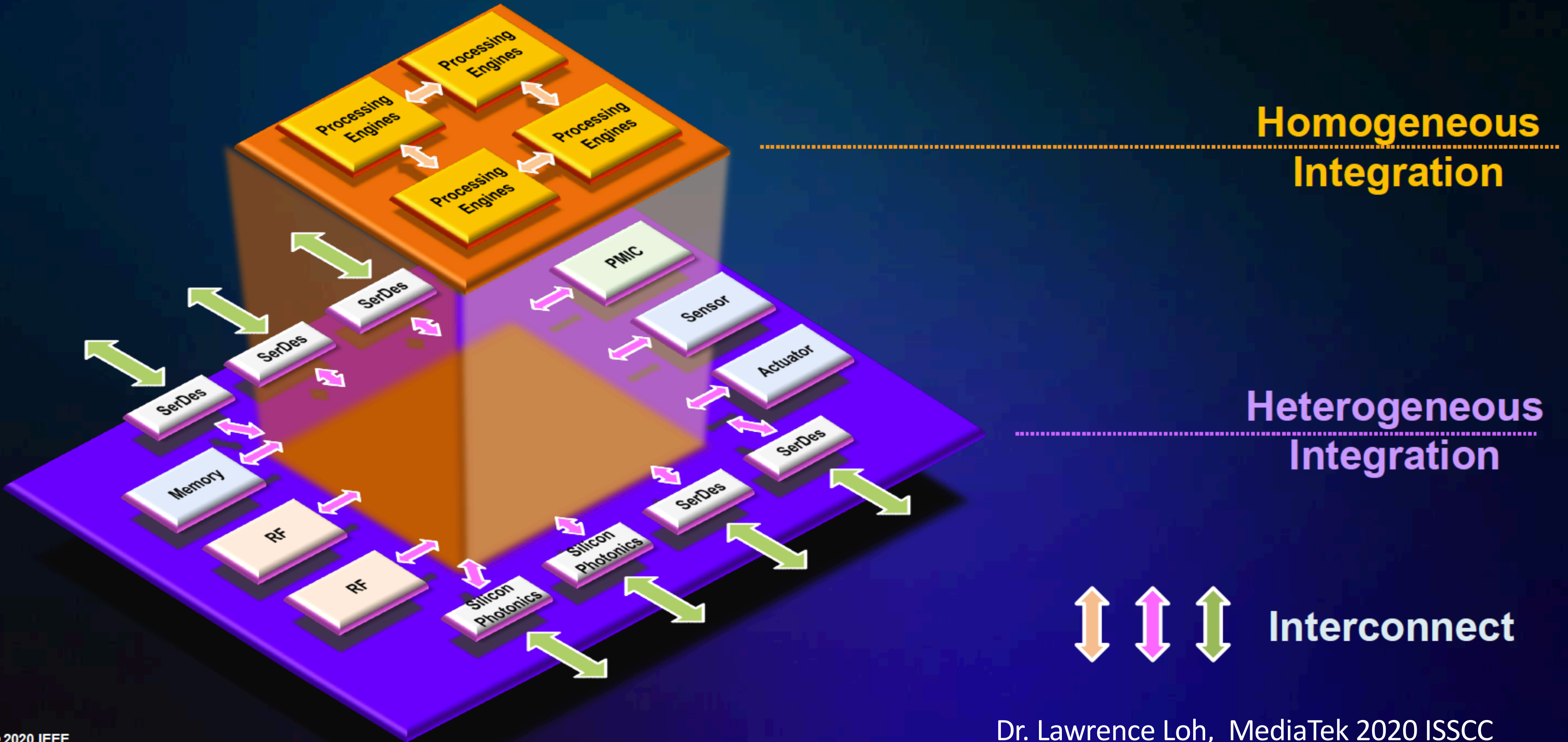


- At 30 GHz, λ/2 = 200 mils, or 5 mm
- Electronics Footprint a Serious Challenge
  - Worse for Dual Pole
- Front-End Function Desired in Beamformer Package
  - PAs and LNAs

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

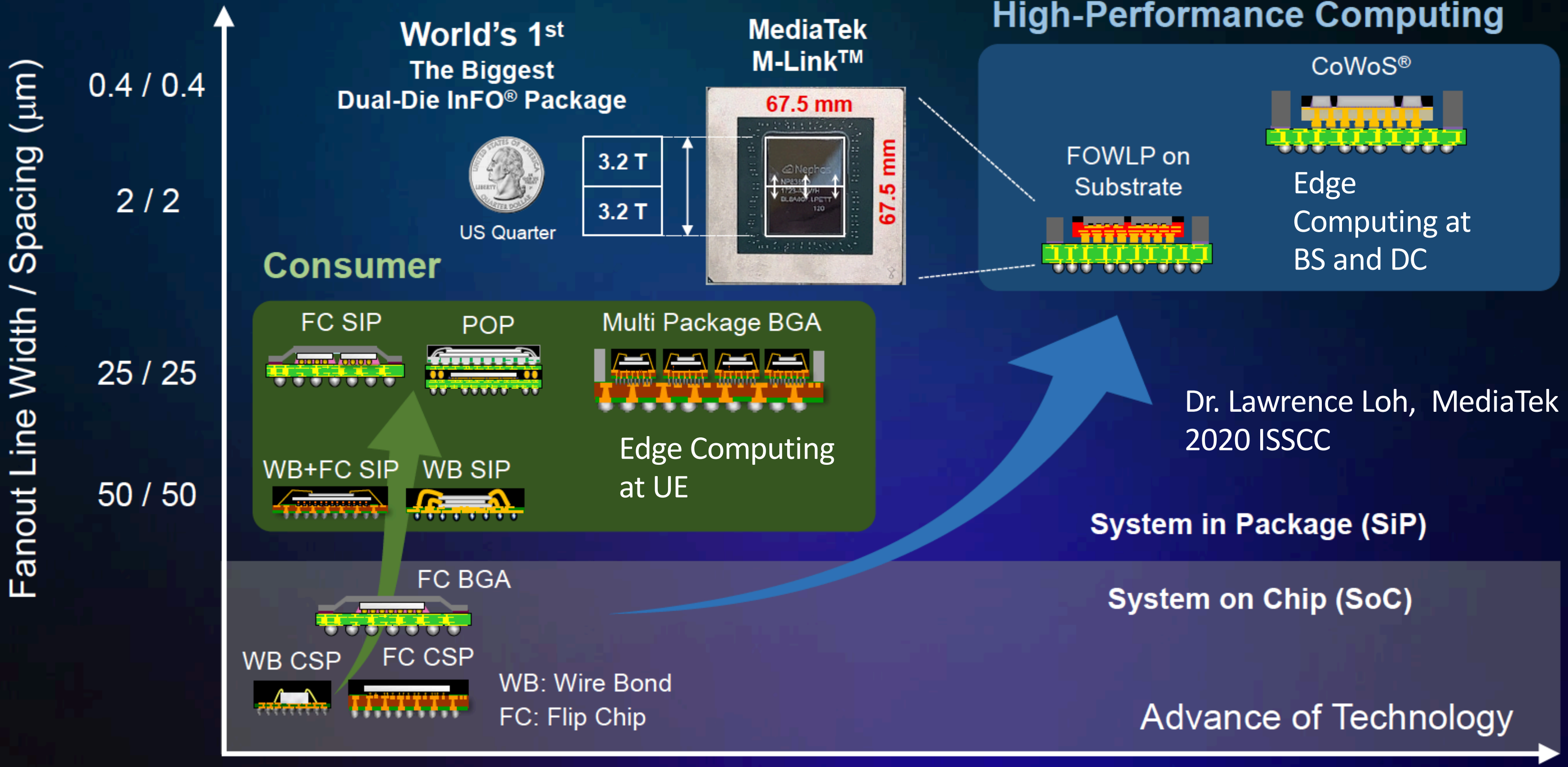
5G Front-End architecture (number of elements, EIRP, Si vs III-V, and Packaging) need to be tailored for each use case

Chiplet : More than Moore



Dr. Lawrence Loh, MediaTek 2020 ISSCC

Advances of Package for Chiplet Integration



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

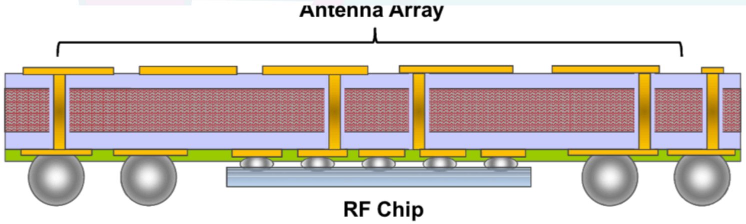


Fig.3. Cross-section view of the mmWave transceiver on flip chip ball grid array (FCBGA) AiP.

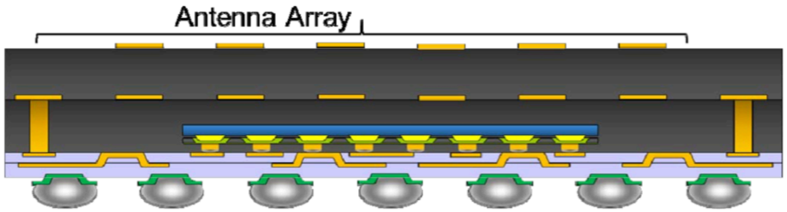
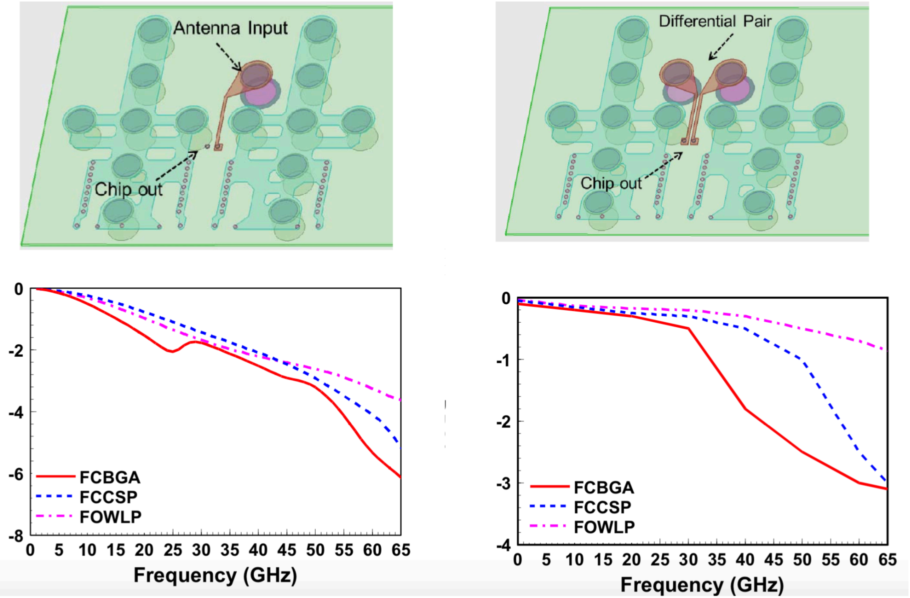
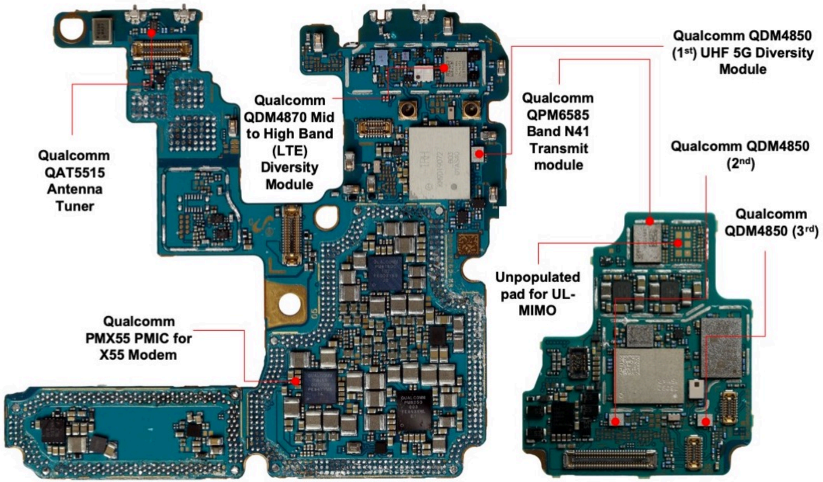


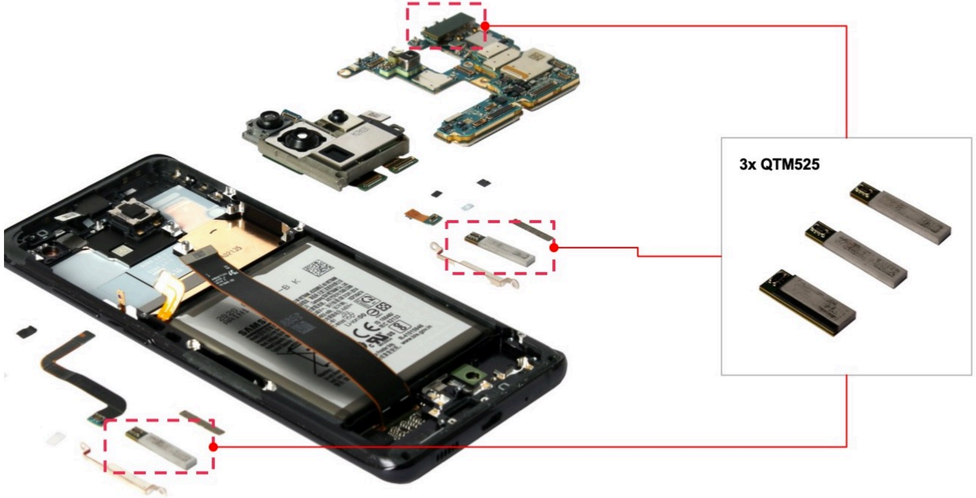
Fig. 8. Geometry of the fan-out Antenna in Package



Sheng-Chi Hsieh et al, ECTC2019, ASE

Samsung S20 Ultra mm-wave 5G Phone Teardown Photos





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

First Gen RFFE Cost Comparison (5G vs LTE)

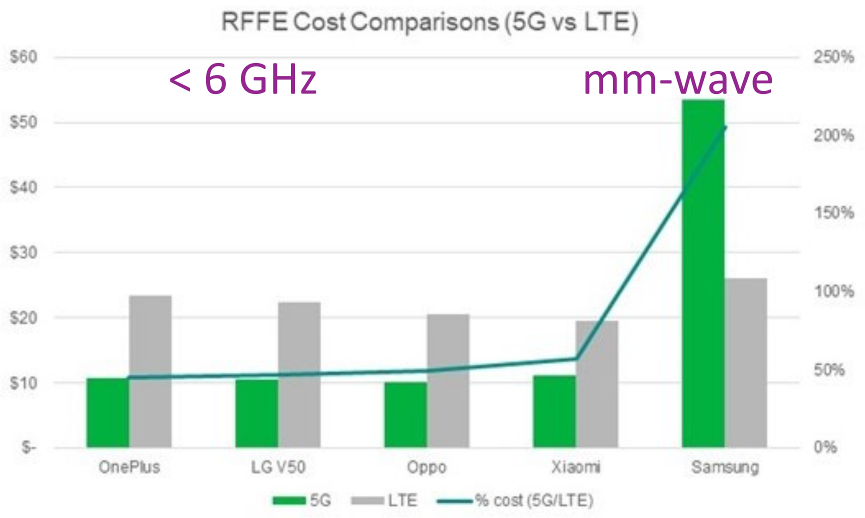


Chart 6 – Component cost comparisons of all 5 Qualcomm 5G designs

- 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

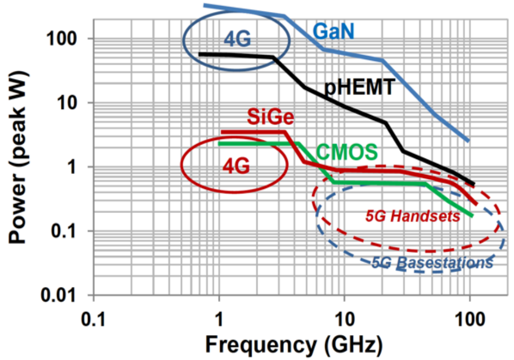
Technology/Capability Gaps and Showstoppers

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

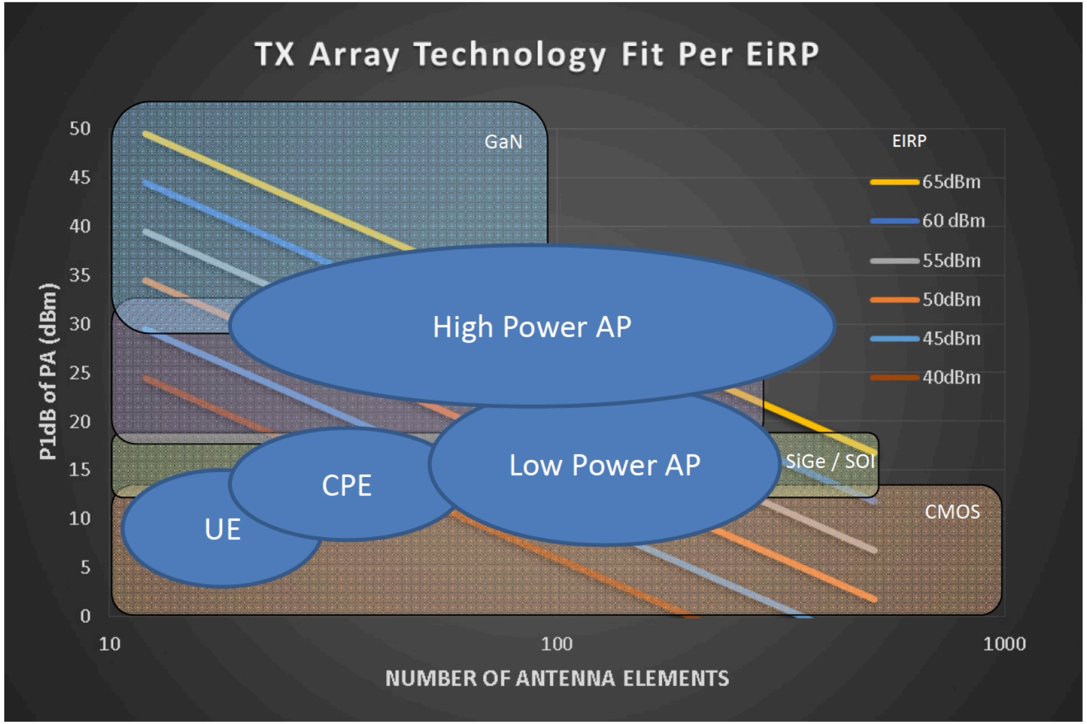
Estimated Power Ranges for 5G TX ICs & *Estimated* Max Power of Different Technologies



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**

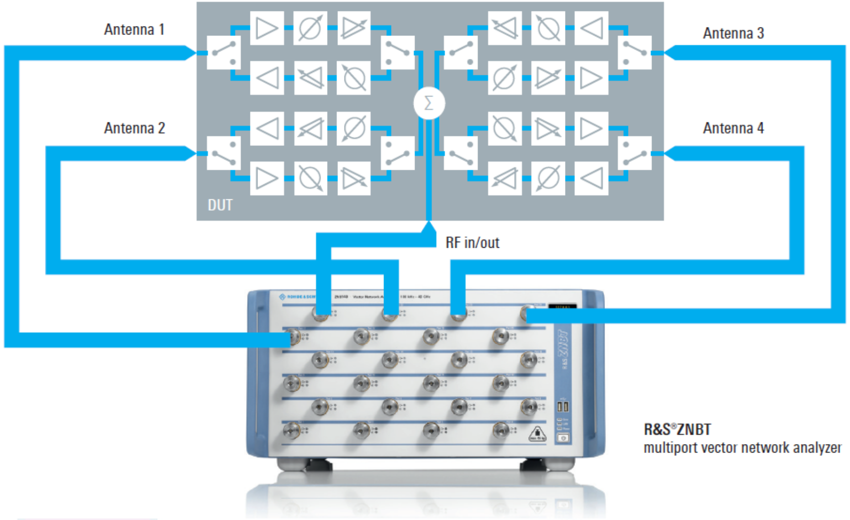
5G Roadmap will address the system trade between Silicon and III-V



Technology/Capability Gaps and Showstoppers

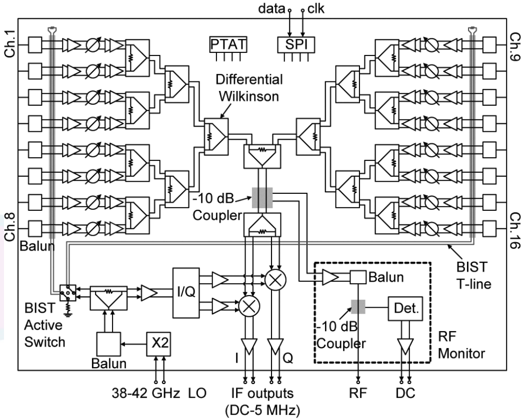
Challenge 3: Low-Cost mmWave Volume Testing

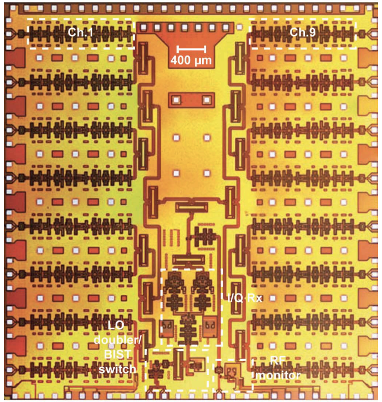
Today: Rack-and-Stack Tester



courtesy Rohde and Schwarz

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





[S-Y Kim, TMTT 2013]

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

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

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 ad 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!

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QUESTIONS?