RF Test Strategies and Solutions for 5G Millimeter Wave Devices

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Teradyne

TestConX™

Virtual Event ● May 11-13, 2020

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What Does it Take to Build a 5G Network?

https://www.shutterstock.com/image-photo/architect-thinks-how-design-house-286105154

What Does it Take to Build a 5G Network?

1. Define the Standard
2. Assign the Spectrum
3. Develop Devices
4. Roll out Infrastructure

and

Test, Test, Test!

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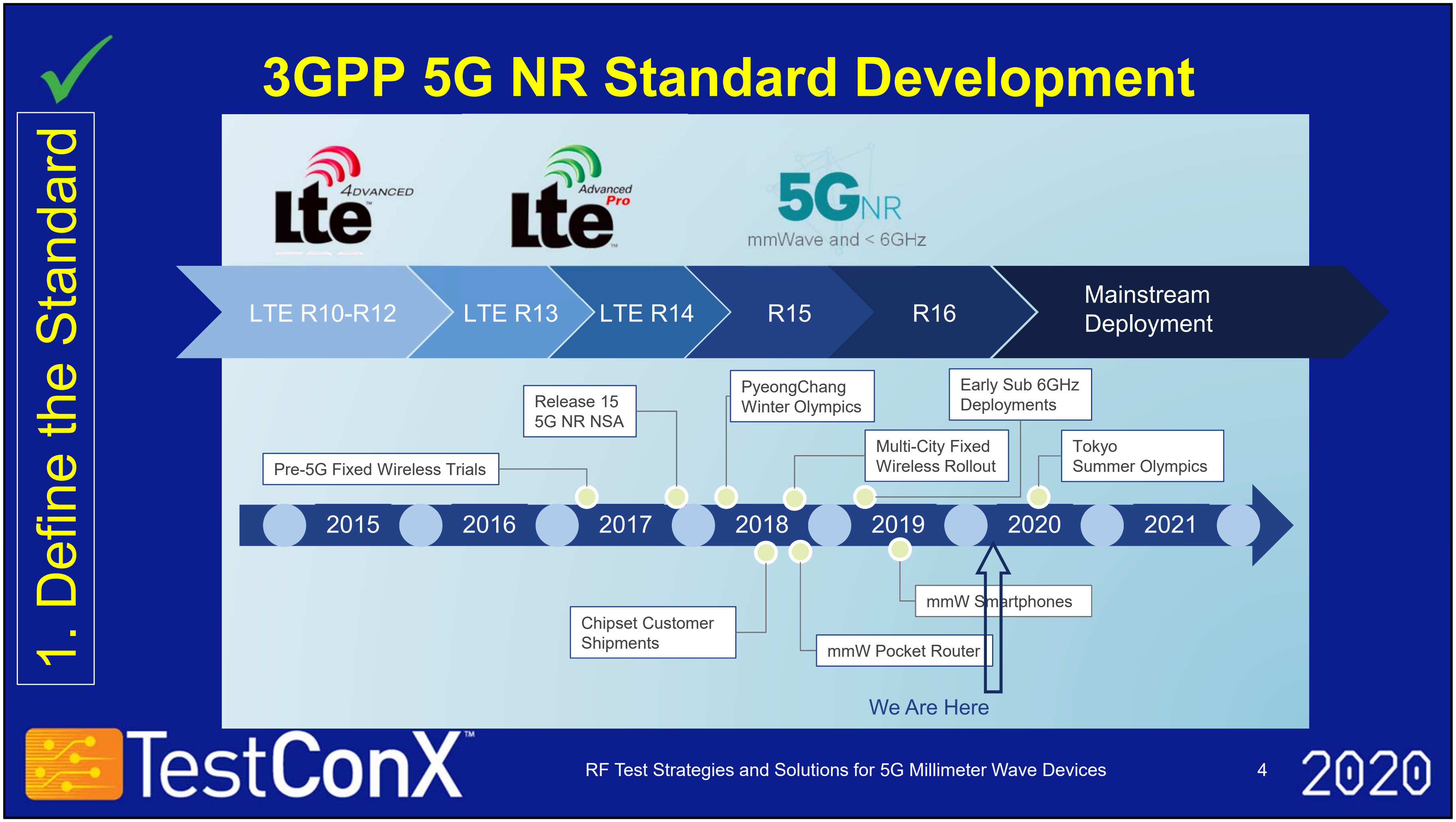
3GPP 5G NR Standard Development
1. Define the Standard
5G NR
mmWave and < 6GHz
LTE R10-R12
LTE R13
LTE R14
R15
R16
Mainstream Deployment
Release 15 5G NR NSA
PyeongChang Winter Olympics
Early Sub 6GHz Deployments
Pre-5G Fixed Wireless Trials
Multi-City Fixed Wireless Rollout
Tokyo Summer Olympics
2015
2016
2017
2018
2019
2020
2021
mmW Smartphones
Chipset Customer Shipments
mmW Pocket Router
We Are Here
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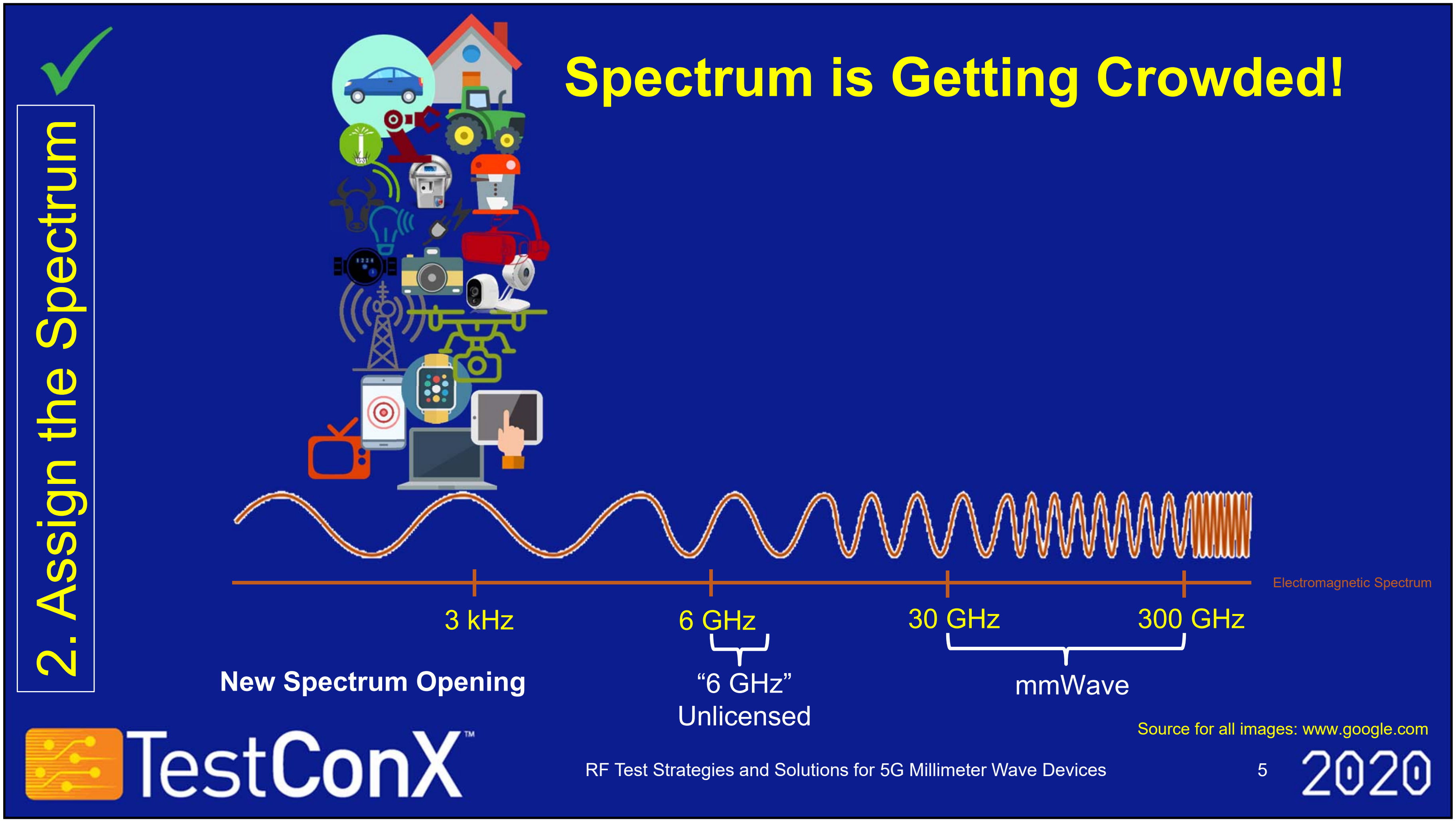
2. Assign the Spectrum
Spectrum is Getting Crowded!
Electromagnetic Spectrum
3 kHz
6 GHz
30 GHz
300 GHz
New Spectrum Opening
"6 GHz"
Unlicensed
mmWave
Source for all images: www.google.com
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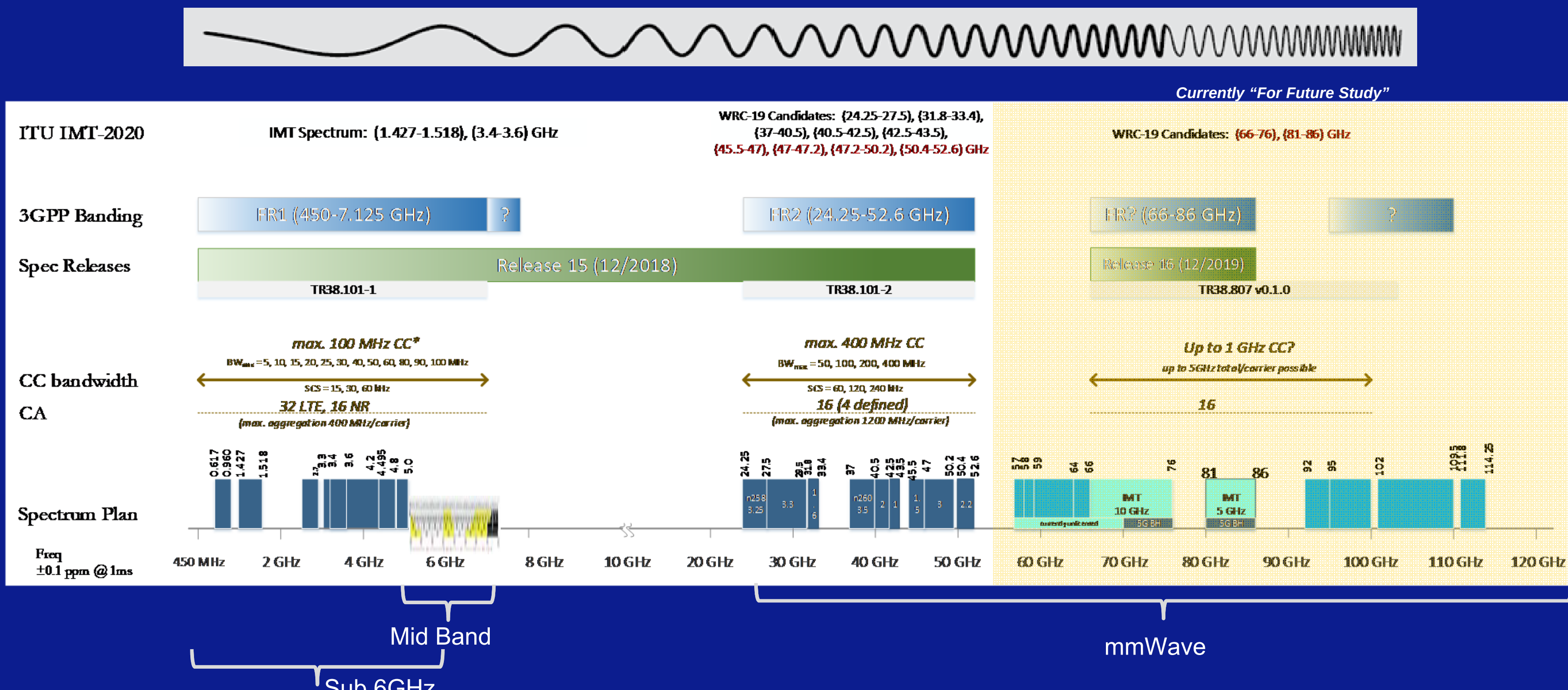
Spectrum and Bandwidth



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Global 5G Spectrum Deployment Plans

Sub-6GHz (FR1) & mmWave (FR2)

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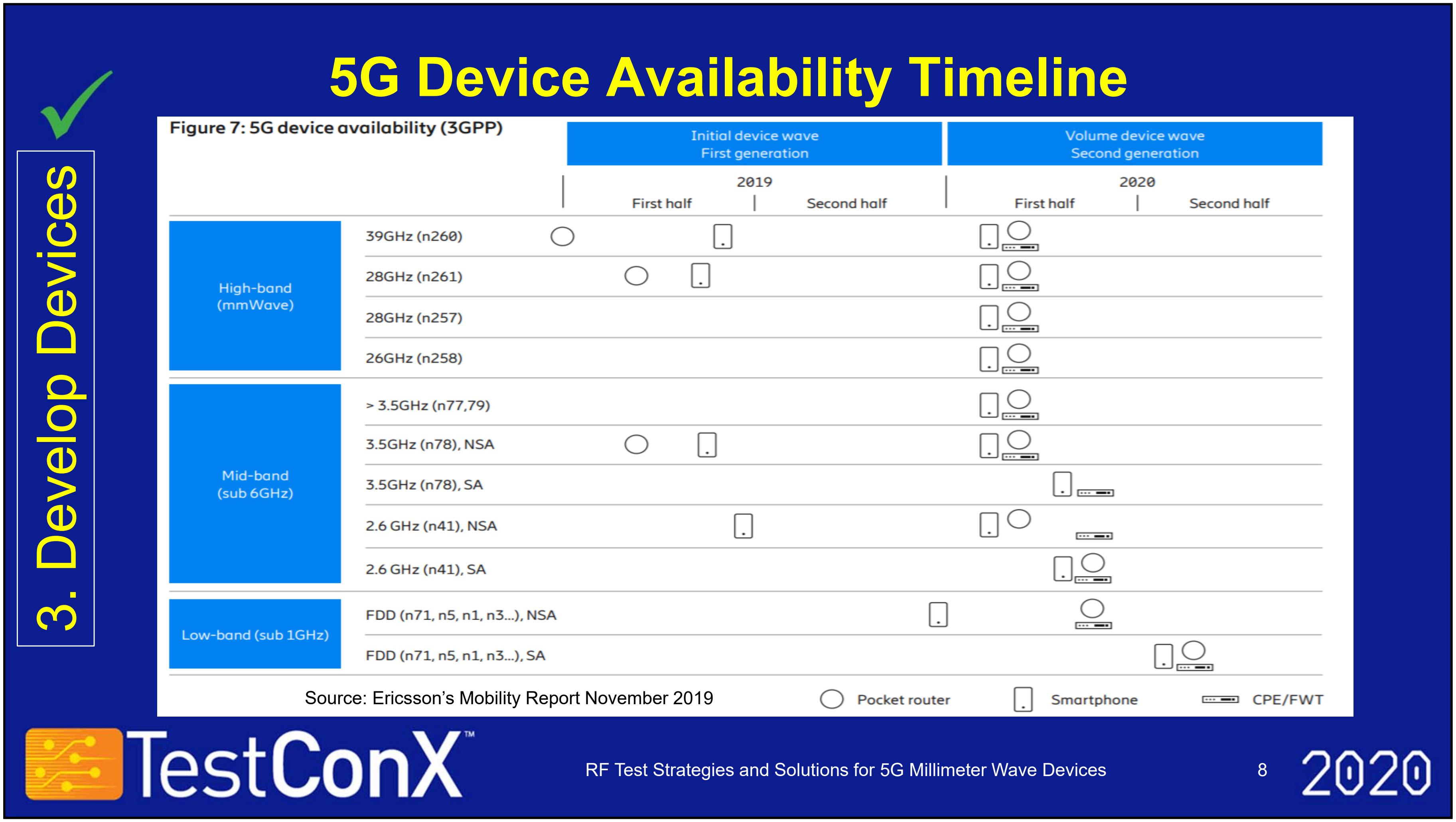
5G Device Availability Timeline
3. Develop Devices
Figure 7: 5G device availability (3GPP)
Initial device wave
First generation
Volume device wave
Second generation
2019
2020
First half
Second half
First half
Second half
High-band (mmWave)
39GHz (n260)
28GHz (n261)
28GHz (n257)
26GHz (n258)
Mid-band (sub 6GHz)
> 3.5GHz (n77,79)
3.5GHz (n78), NSA
3.5GHz (n78), SA
2.6 GHz (n41), NSA
2.6 GHz (n41), SA
Low-band (sub 1GHz)
FDD (n71, n5, n1, n3...), NSA
FDD (n71, n5, n1, n3...), SA
Source: Ericsson's Mobility Report November 2019
Pocket router
Smartphone
CPE/FWT
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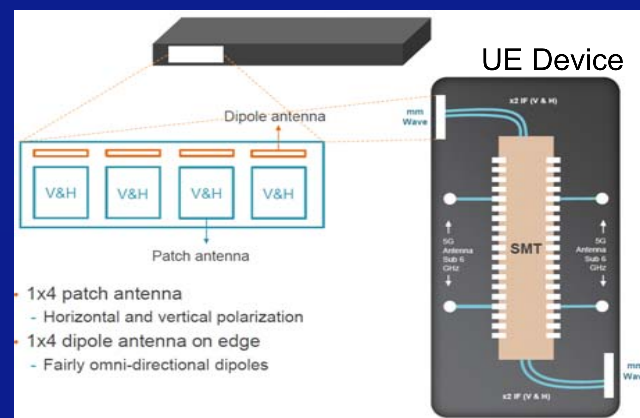
mmWave

$$\lambda = \frac{c}{f}$$

- Consumer products emerging between 24 GHz and 86+ GHz
- mmWave make < 2 mm antenna sizes possible
- Enables phased antenna arrays (1x4, 2x2, 4x4, 8x8, etc.)



5G Device Announcements Examples

Brand	Model	Sub 6GHz or mmWave?	Carrier Network	Brand
Motorola	Z3 5G mod	mmWave	Verizon	Motorola
Samsung	Galaxy S10 5G (1st gen)	mmWave	Verizon / AT&T LG U+ / KT / SK	Samsung
Samsung	Galaxy S10 5G (2nd gen)	mmWave & Sub 6GHz	US: AT&T & Verizon 2020	Samsung
Samsung	Galaxy Fold	mmWave	Verizon	Samsung
LG	V50 ThinQ 5G	mmWave	Verizon / Sprint	LG
Xiaomi	Mi Mix3 5G	mmWave	Orange, 3, Sunrise, Telefonica, Tim and Vodafone	Xiaomi
ZTE	Axon 10 Pro 5G		China & Europe	ZTE
Netgear	Nighthawk (mobile hotspot)	mmWave	AT&T	Netgear
Inseego	Verizon brand	mmWave	Verizon	Inseego
Huawei	Mate X	Sub 6GHz	China carriers to start	Huawei


Examples of Mobile 5G Device Announcements
Moto Z3 w/ 5G mod
LG V50 ThinQ 5G
ZTE Axon 10 Pro 5G
OPPO Reno 5G
Samsung Galaxy S10 5G
Samsung Galaxy Fold
Huawei Mate X
Xiaomi Mi Mix3 5G
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Source for all images: www.google.com

Examples of Mobile Hotspot and CPE Devices Announcements

Netgear Nighthawk (mobile hotspot)
Source: www.google.com

Huawei (mobile hotspot)

Huawei (CPE)

Inseego (mobile hotspot)
Source: www.google.com

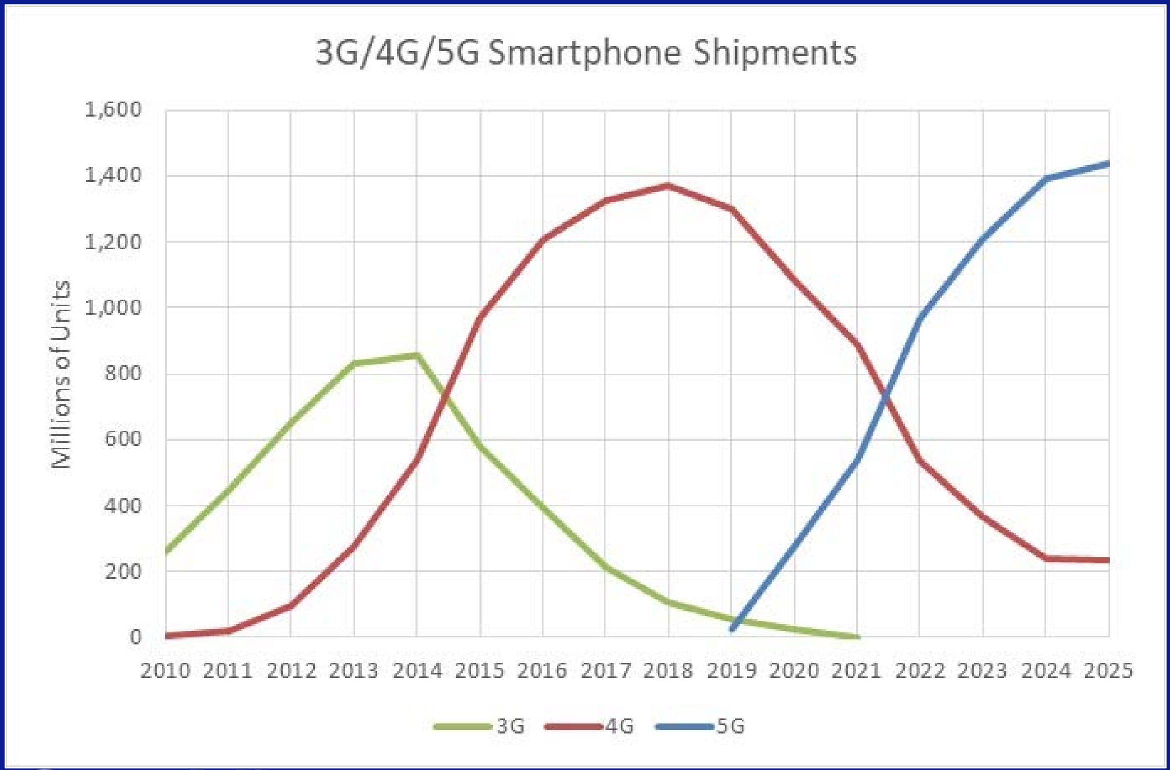
Samsung (CPE)
Source: www.google.com

4. Roll out Infrastructure

Global 5G Infrastructure Deployments

Source: https://qualcomm.com/documents/2019-future-5g-presentation

5G Infrastructure Will Have a Steeper Ramp Than 3G/4G!



Source: 3G/4G and 5G projections from Statista, IHS, CLSA

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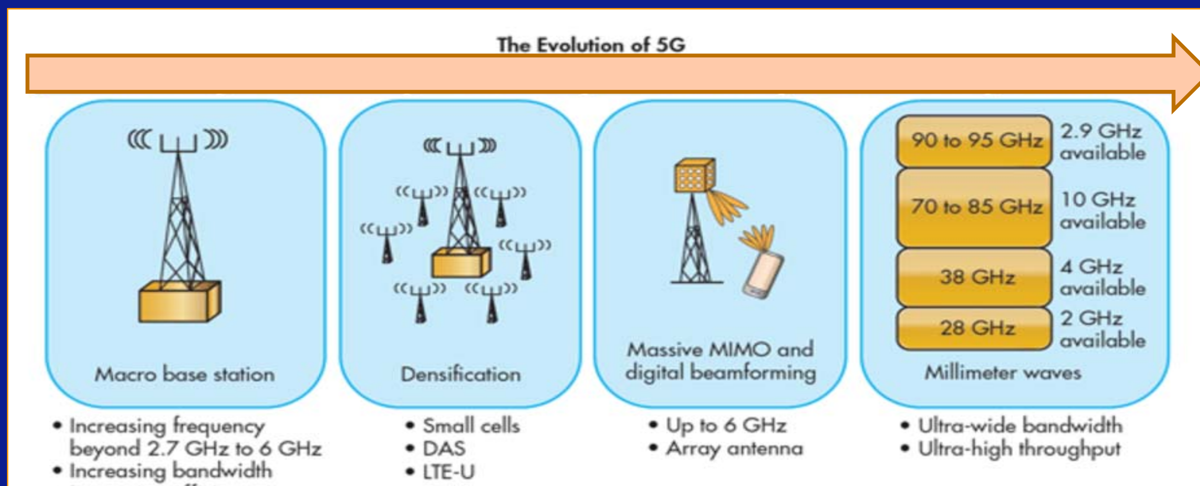
5G Capacity Enablers: mMIMO, Small Cells & mmWave

5G Channel Capacity (bps) = (BW)* $\log_2$ (1 + SINR[1])

mmWave Value Proposition:
Much higher BW than Sub 6 GHz

Small Cells Value Proposition:
Higher SINR with Massive MIMO + Beamforming at < 6GHz and mmWave



Source: https://www.qorvo.com/design-hub/blog/small-cell-networks-and-the-evolution-of-5g

x1600 times gain in capacity expected with Small Cells Densification

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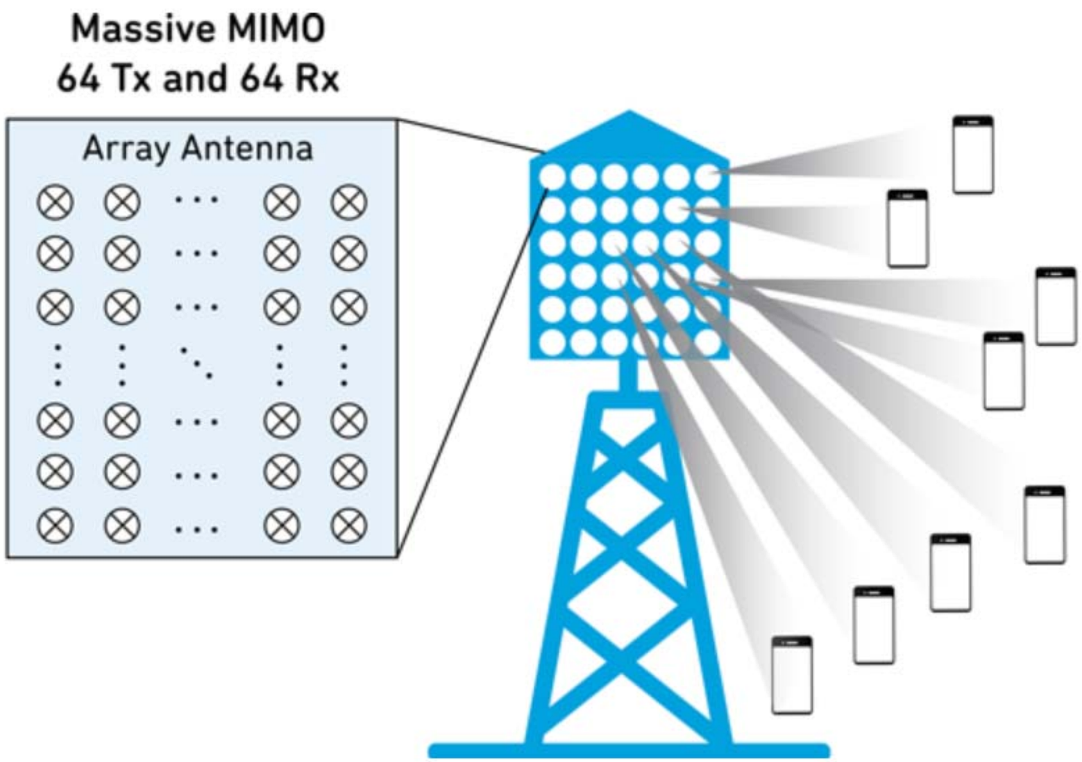
5G Infrastructure mMIMO



- More active antenna elements
- More focused energy
- Less interference
- More spatial multiplexing layers
- Better cellular throughput and coverage
- Large number of users served simultaneously
- Introduces 2 dimensional beamforming

Source: https://www.mwrf.com/semiconductors/realizing-5g-sub-6-ghz-massive-mimo-using-gan#close-olyticsmodal

What Does it Take to Build a 5G Network?

1. Define the Standard ✓
2. Assign the Spectrum ✓
3. Develop Devices ✓
4. Roll out Infrastructure ✓

and

Test, Test, Test!

5G NR Key Parameters

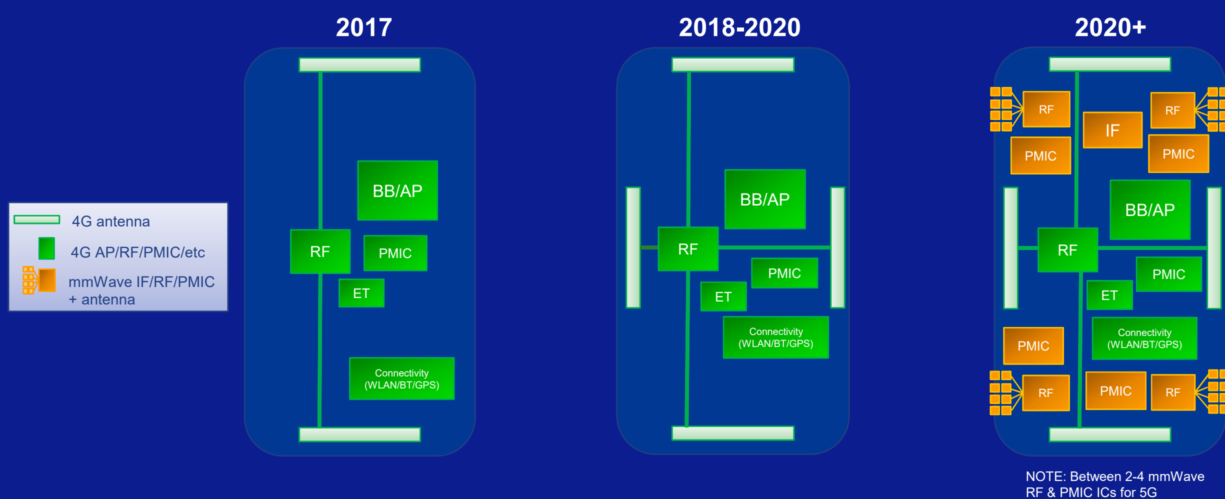
Item	Frequency Range 1 (FR1)	Frequency Range 2 (FR2)
Known As	Sub 6 GHz	mmWave
Frequency Range	450 MHz - 6000 MHz	24250 MHz - 52600 MHz
Duplex Mode	FDD, TDD	TDD
Subcarrier Spacing	15, 30, 60 KHz	60, 120 KHz
Bandwidth	5, 10, 15, 20, 25, 30, 40, 50, 60, 80, 100 MHz	50, 100, 200, 400 MHz
MIMO	DL: 8x8 UL: 4x4	DL: 2x2 UL: 2x2
MIMO Method	Spatial Multiplexing for higher Throughput	Beamforming for better SNR
Radio Frame Duration	10ms	
Subframe Duration	1ms	
Modulation	pi/2-BPSK, QPSK, 16QAM, 64QAM, 256QAM	pi/2-BPSK, QPSK, 16QAM, 64QAM
Access	DL: CP-OFDM UL: CP-OFDM, DFT-s-OFDM	
Carrier Aggregation	16 carriers maximum	
Channel Coding	Polar Codes, LDPC Codes	

Higher Frequencies

Higher Bandwidth

Maximum CC (Component Carrier) bandwidth is 100 MHz for FR1 and 400 MHz for FR2: *a 5x to 20x improvement over 4G LTE!*

Anatomy of a Smartphone – The Impact of 5G



MIMO	2x2 MIMO	4x4 MIMO	4x4 MIMO + Patch Arrays for mmWave
Data rates	450-600 Mbps	Up to 1,000 Mbps	10,000 Mbps
Carrier Frequency	< 6GHz Frequencies	< 6GHz Frequencies	< 6GHz + mmWave Frequencies
CC Bandwidth	Up to 20MHz CC bandwidth	Up to 100MHz CC bandwidth	Up to 100MHz CC bandwidth
Radio "Cores"	3DL/2UL	6DL/2UL	9DLP (Component Carriers)
Silicon Count	5-7 Major ICs (*depending on AP/BB integration*)	5-7 Major ICs (*depending on AP/BB integration*)	**9-15 Major ICs** (*depending on AP/BB integration & mmWave RF devices*)

5G complexity adds more risk of field failures

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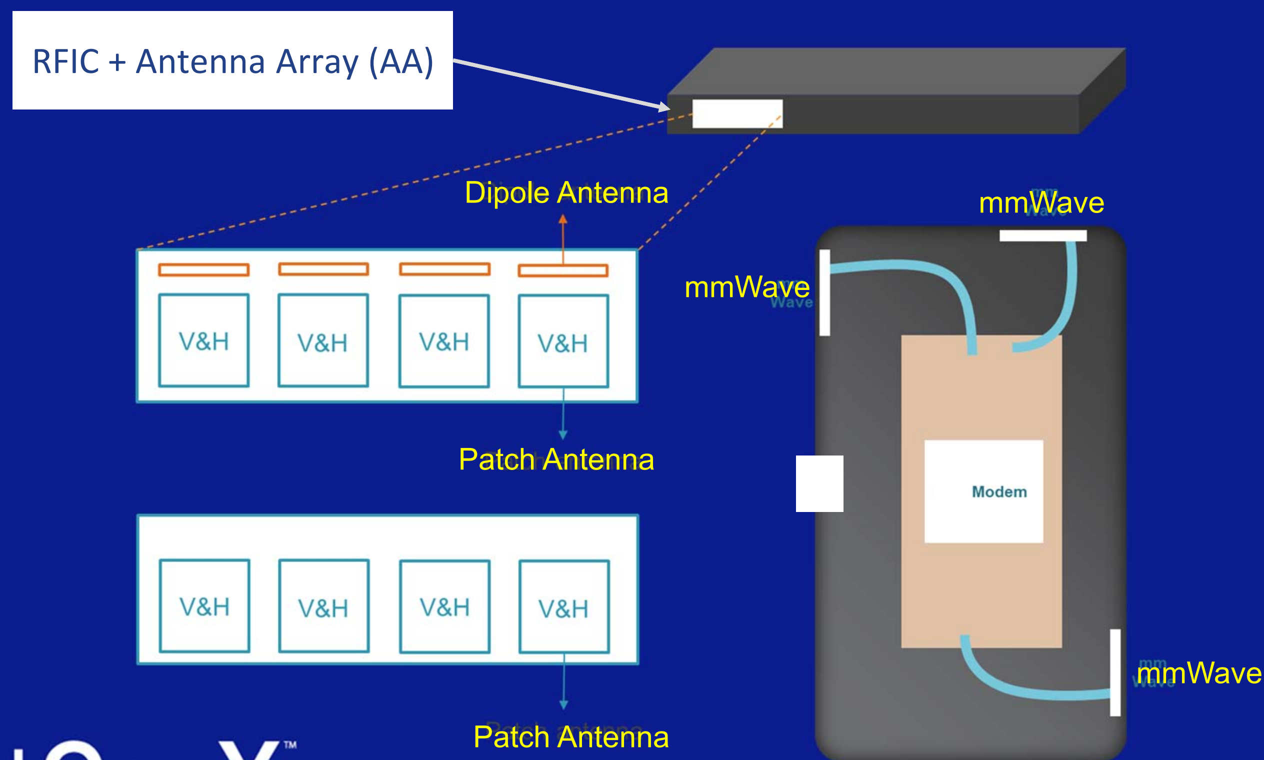
5G millimeter wave Devices Require Some Form of "over the air" (OTA) Test as the Antennas are Packaged with the RF IC

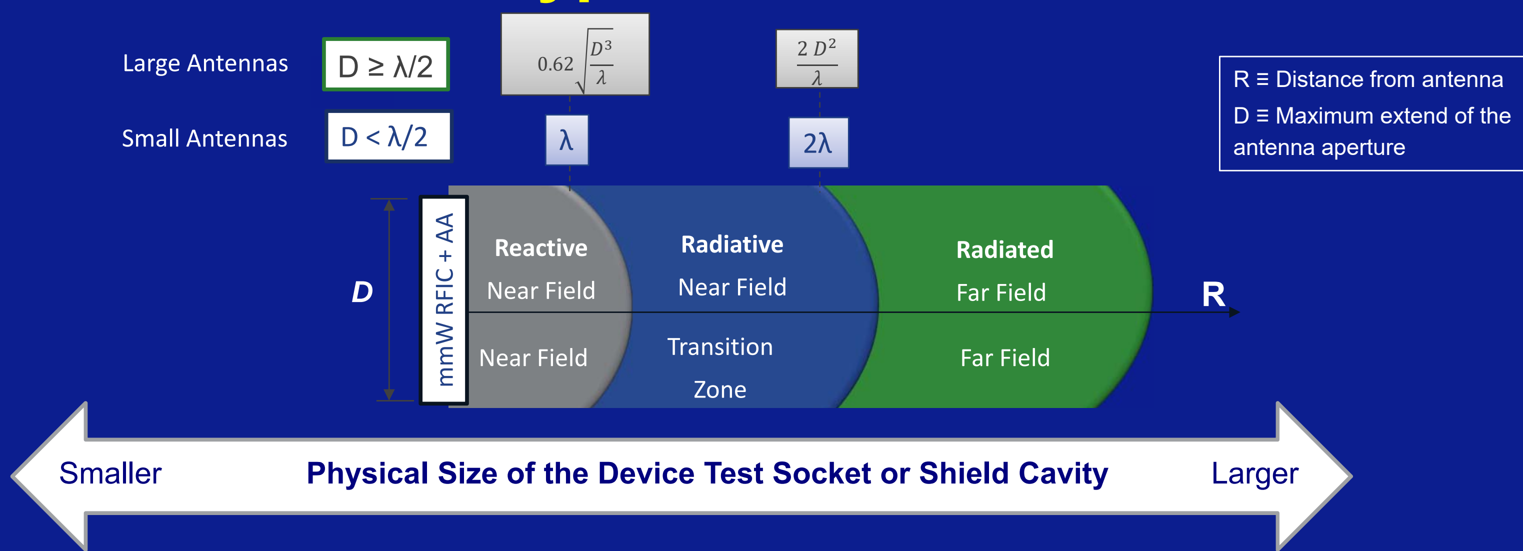


Why Test?

If 5G fails, your brand fails.

- **5G mmWave** devices in very early product life cycle stage, performance risks need sound test strategies
- **5G mmWave premium phones** will demand **0 DPPM** quality levels
- **Need to establish a reliable 5G brand** as Chinese vendors market share increases
- **High quality brand strategy** requires more functional tests at probe and module insertions
- **Poor upstream** module, sub-assembly & final product **OTA yields** drive more functional test
- Characterization tests uncover **failure mechanisms**
- **5G use cases that drive** volume and **performance** turn drive more device functional testing
- Any "emergency" massive field failures require functional-test-ready ATE on site

What Type of "OTA" Test?

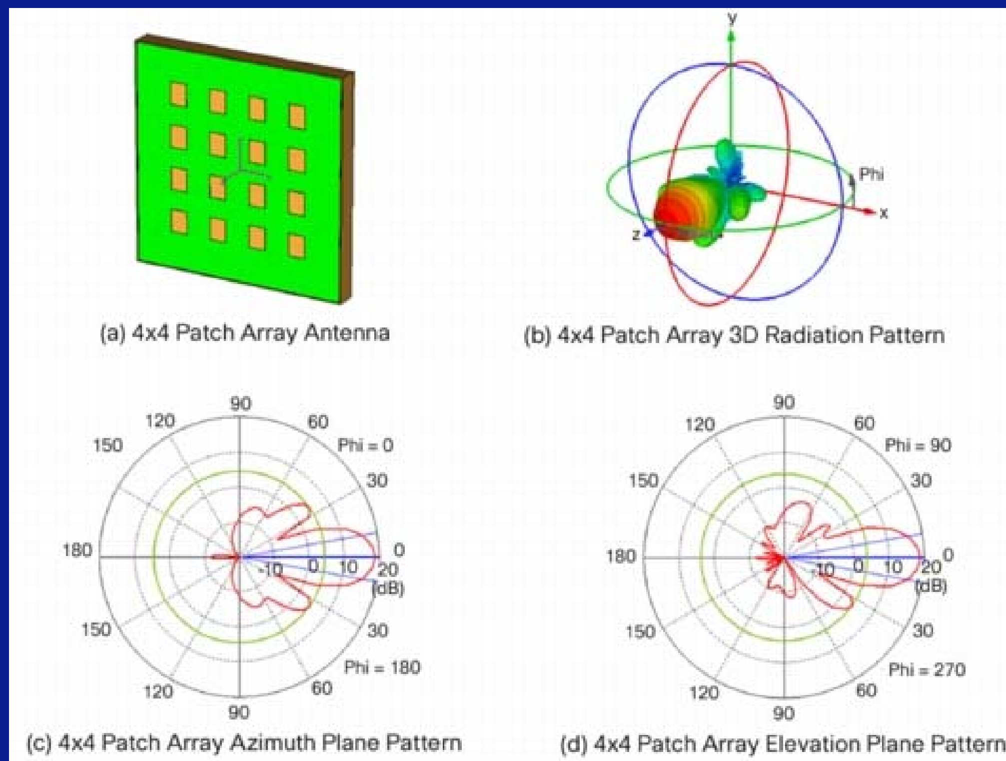


Reactive near-field region: It is the region where stored energy dominates. These reactive fields are generally created by strong **EM coupling** within the antenna or between antennas and very nearby electrical components. No radiative energy exists.

Radiative near-field region (NF): This is the region where the near fields still exist but is not dominant. Radiative near-fields start to dominate. However, the shape of **the radiation pattern may still vary appreciably with distance.**

Far-field region (FF): the shape of the radiation pattern does not change with distance. The spherical fields propagating outward can be considered as plane waves.

Example of Path Antenna Array Radiation Pattern



(a) 4x4 Patch Array Antenna

(b) 4x4 Patch Array 3D Radiation Pattern

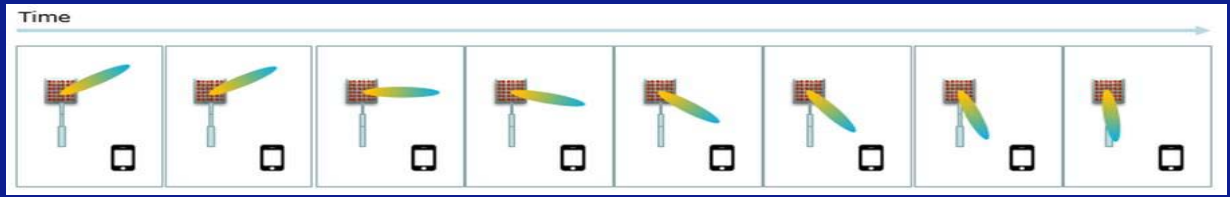
(c) 4x4 Patch Array Azimuth Plane Pattern

(d) 4x4 Patch Array Elevation Plane Pattern

https://e2e.ti.com/support/wireless-connectivity/bluetooth/f/538/t/839954

Beamforming with Phased Antenna Arrays

- Radiation pattern of antenna is fixed by design, thus difficult to control it or change it, unless antenna geometry is changed
- Phased antenna arrays allows for beamforming – the control of the radiation pattern on a given direction *on the fly*
  - ***Multiple antennas***
  - ***Superposition of the waves from each antenna***
  - Phased array ***can control its radiation pattern***
  - M***ore antenna elements*** it has → larger its antenna aperture → ***larger the gain*** it has in the main lobe, and ***the narrower the beam***

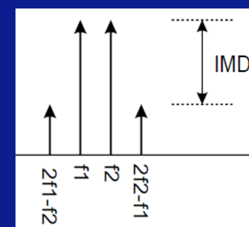


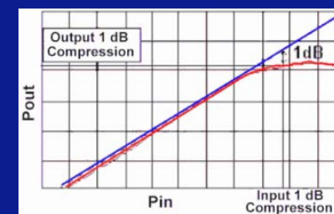
https://www.sharetechnote.com/html/5G/5G_Phy_BeamManagement.html

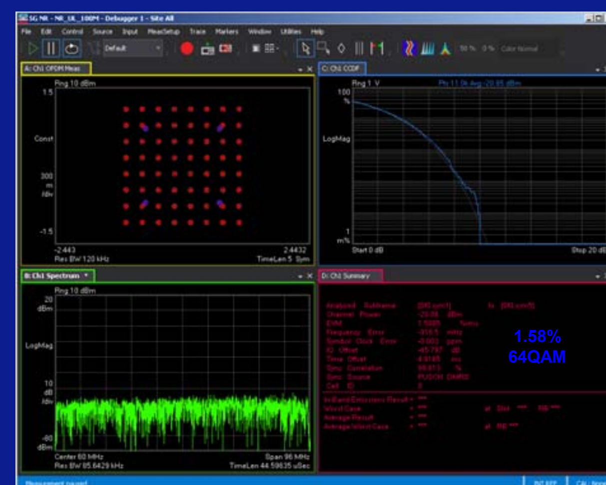
What to Test?

- mmWave RFIC
  - Gain
  - P1dB and IP3
  - Band pass filter(channel select) gain/flatness/out-band attenuation
  - PLL lock
  - ACLR
  - EVM
  - Phase trimming
  - Beamforming?
  - Others (DC, leakage, pattern-scan and BIST)

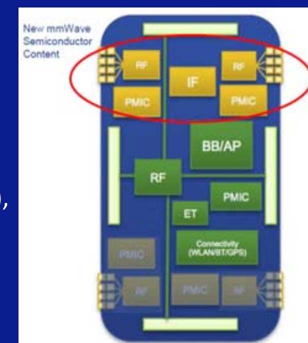
- mmWave RFBB (IFIC)
  - Gain
  - IP3
  - Low pass filter(channel select) gain/flatness/out-band attenuation
  - PLL lock
  - ACLR
  - EVM
  - IQ mismatch / IQ cal(phase and gain cal for Image rejection and carrier suppression)
  - Others (DC, leakage, pattern-scan and BIST)







5G mmWave is Changing Traditional Cell Phone Architecture and Test Needs

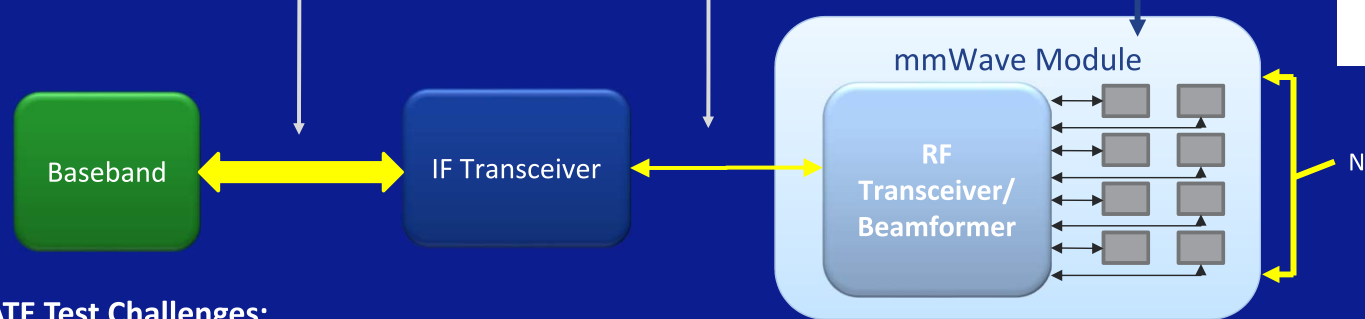


Interface Characteristics:

DigRF/Analog IQ
Up to 16Gbps

5G IF
6-15 GHz (non-standard)
BW: 100MHz/400MHz/800MHz

5G RF mmWave
(24.25-27.5), (31.8-33.4), (37-40.5), (40.5-42.5), (42.5-43.5) GHz
BW: 100MHz/400MHz/800MHz

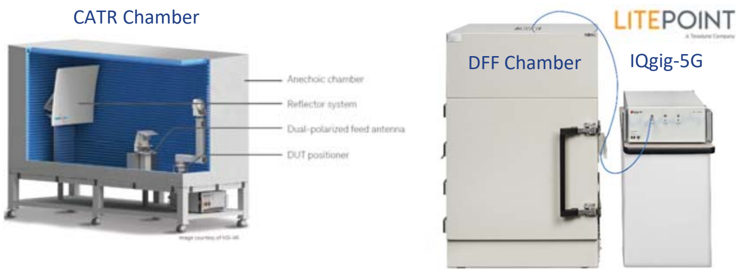


ATE Test Challenges:

- Use of antenna arrays require **higher port count** at mmWave frequencies
- Signal beamforming require **new and innovative test techniques**
- Exponential volume growth drives **site count and throughput improvements** at record pace

5G mmWave Test Strategies in the Lab

R&D



- **Signaling and non-signaling testing required**
- VNA and VSA/VSG test equipment
- Choice of either Compact Antenna Test Range (CATR) or Direct Far Field (DFF) chamber depending on AA size.
- IF and mmWave frequencies performance test at full BW
- Different sized chambers depending on DUT size
- **Beamforming performance characterization test insertion**

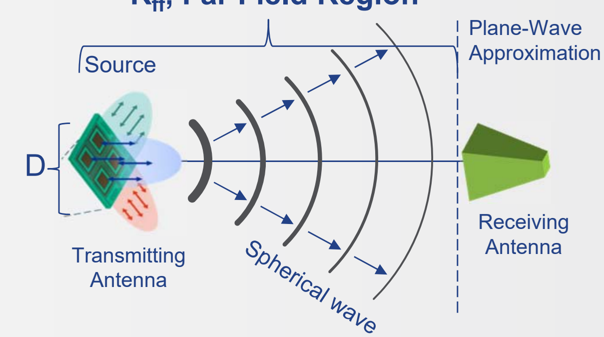
DVT

- **Non-signaling test**
- VNA and/or VSA/VSG test equipment
- Primarily a mmWave test insertion
- Different sized DFF chambers depending on AA size
- **Beamforming verification test**
- Temperature testing may be required

How Big a Chamber or Shield Box for OTA Far Field Testing?

It depends on the size of the antenna array and the application

R_{ff}, Far Field Region



The far-field region is at a distance R where the wave may be considered to be a plane wave

$$R_{ff} = \frac{2D^2}{\lambda}$$

D = Maximum effective size of the antenna

λ = Wavelength of the signal

Examples for R_{ff} at 28 GHz and 39 GHz

Freq (GHz): **28** Wavelength (mm): 10.7
Assume lambda/2 antenna size

Antenna Array	2x2	3x3	4x4	5x5	6x6	7x7	8x8
Aperture D (mm)	15	23	30	38	45	53	61
Approx Far Field (cm)	5	10	18	27	39	53	69

Freq (GHz): **39** Wavelength (mm): 7.7
Assume lambda/2 antenna size

Antenna Array	2x2	3x3	4x4	5x5	6x6	7x7	8x8
Aperture D (mm)	11	16	22	27	33	38	44
Approx Far Field (cm)	4	7	13	20	28	38	50

For UE 2x2 Antenna, **far field** is < 6cm
(requires comparable receiving antenna D)

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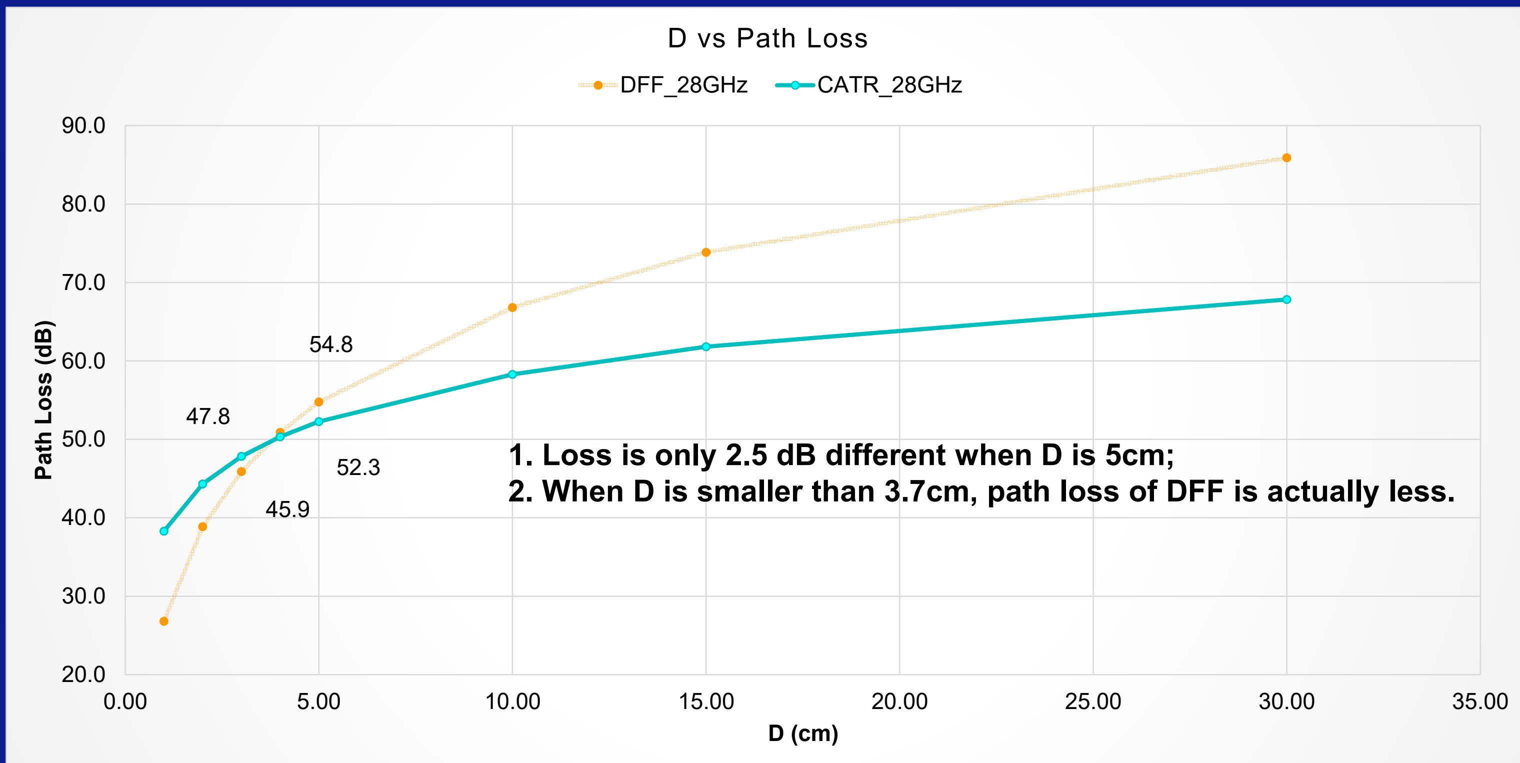
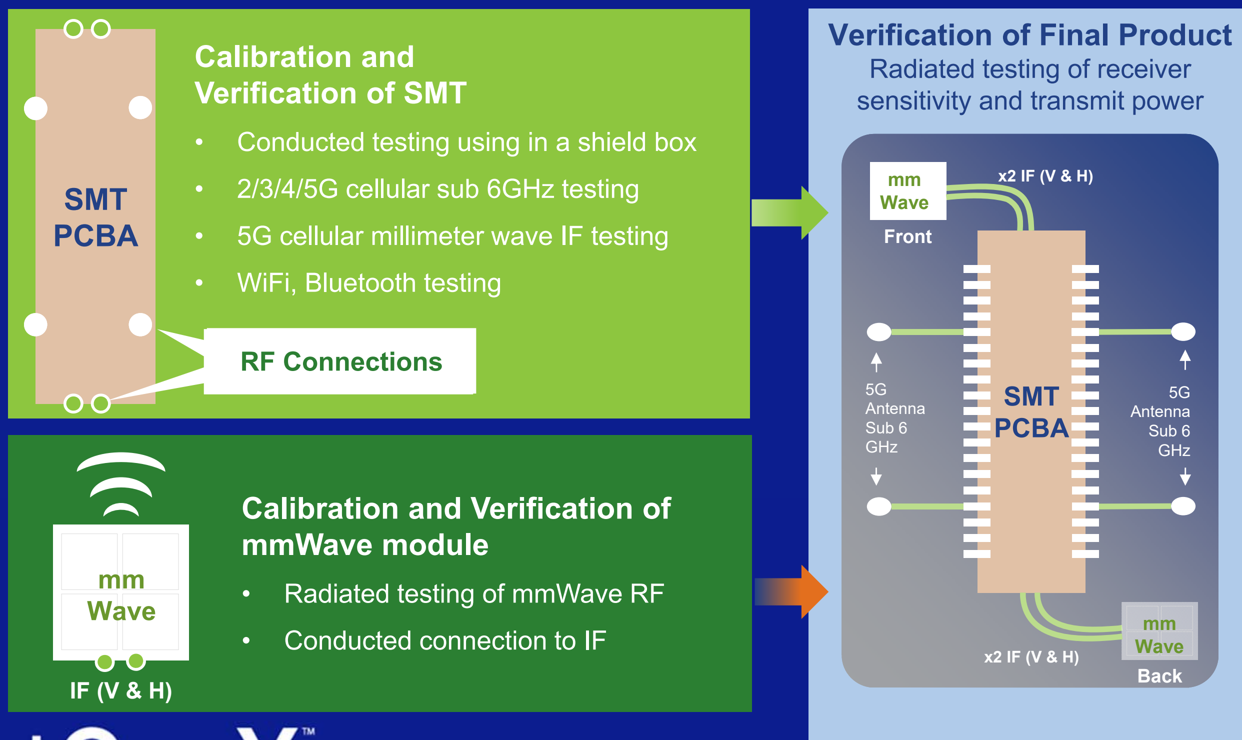
Far-field Criteria of CATR vs DFF



Manufacturing Test Flow for UE Components



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5G mmWave Test Strategies in Mass Production

UltraFLEX mmWave ATE

IQgig-5G

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Silicon Wafer Test → Module Assembly (AiP or AoB) → Module "OTA Continuity" Test → Module Functional OTA Test → Sub-Assembly PCBA OTA Test → Final Product OTA Test

Silicon Wafer Test

Verify performance in order to maximize upstream test yields

- **ATE Probe**
- CW mmWave functional test
- DC/Digital
- BIST
- Tri-Temp for 5G RAN

Module Assembly (AiP or AoB)

Need 0 DPPM for mmWave Antenna Assembly

- **X-Ray Inspection** for
- mmWave antennas
- AiP vs AoB assembly yields?
- Multiple SKUs for different frequency bands

Module "OTA Continuity" Test

Need 0 DPPM for mmWave Antenna Radiation

- **ATE Handler**
- OTA Socket
- "Continuity" test for dipole and patch antennas
- Limited functional tests
- Multiple SKUs

Module Functional OTA Test

Need 0 DPPM for mmWave module performance

- **Functional Test**
- OTA Socket or shield box
- OTA NF or FF
- Full functional test
- Beamforming corner tests (FF)
- Multiple SKUs
- Tri-Temp for 5G RAN

Sub-Assembly PCBA OTA Test

Need mmWave performance test of sub-assembly antenna interaction

- **System Level Test**
- OTA Far Field
- Full Functional Test
- Beamforming corner tests
- Multiple SKUs
- Can add value if calibration factors can be added

Final Product OTA Test

Need 0 RMA. Need mmWave performance test and calibration of final assembly antenna interaction.

- **System Level Test**
- OTA Far Field
- Full Functional Test
- Full CC BW EVM Test
- Full CA Test Possible
- Beamforming calibration
- Multiple SKUs
- Tri-Temp for 5G RAN

Must	Likely	Optional

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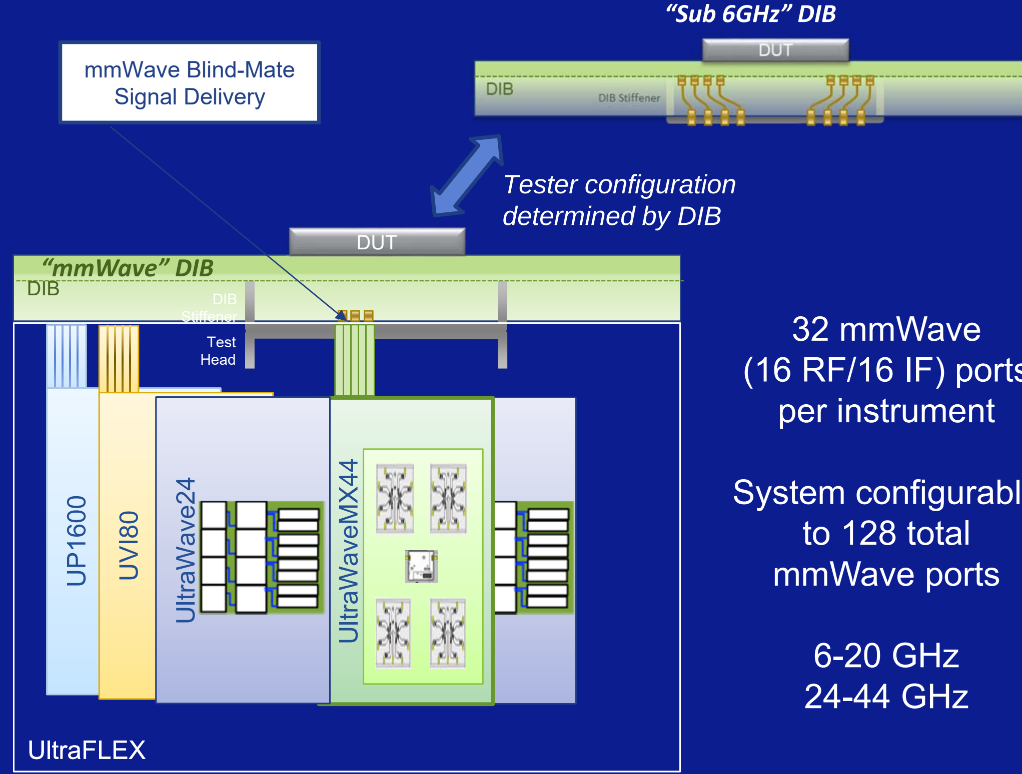
Need ATE with a Simple Upgrade from Sub-6 GHz to mmWave: *UltraWaveMX44*

- Zero change to existing DIB load board standard
- No system reconfiguration required to switch between sub-6GHz and mmWave applications
- Performance specified at blind-mate with fully integrated calibrations
- No change to docking or Z-height



32 mmWave (16 RF/16 IF) ports per instrument

System configurable to 128 total mmWave ports

6-20 GHz
24-44 GHz

https://www.teradyne.com/products/test-solutions/semiconductor-test/ultraflex-mmwave-instruments

Summary

- The 5G Era has arrived
- 5G devices have 2-3 times more ICs than 3G/4G devices
- mMIMO will significantly increase the RF transceiver content in 5G infrastructure base stations and small cells
- 5G is changing the strategy for device testing
  - Teradyne millimeter wave test solutions are at the forefront of the 5G Era

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1. Define the Standard ✓
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and

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✓ **UltraFLEX mmWave ATE**

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✓ **IQgig-5G mmWave**

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