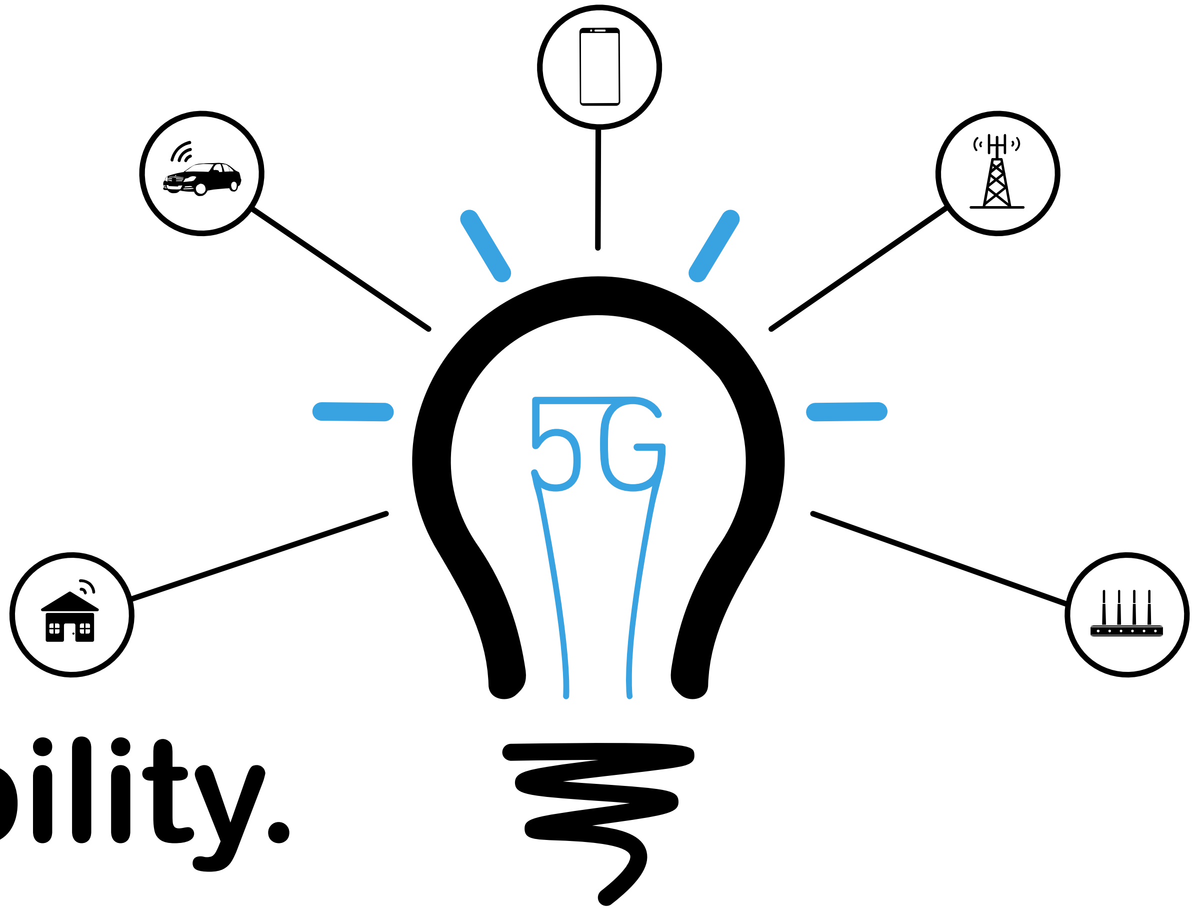
qorvo
all around you



5G: More Capability. More Complexity.

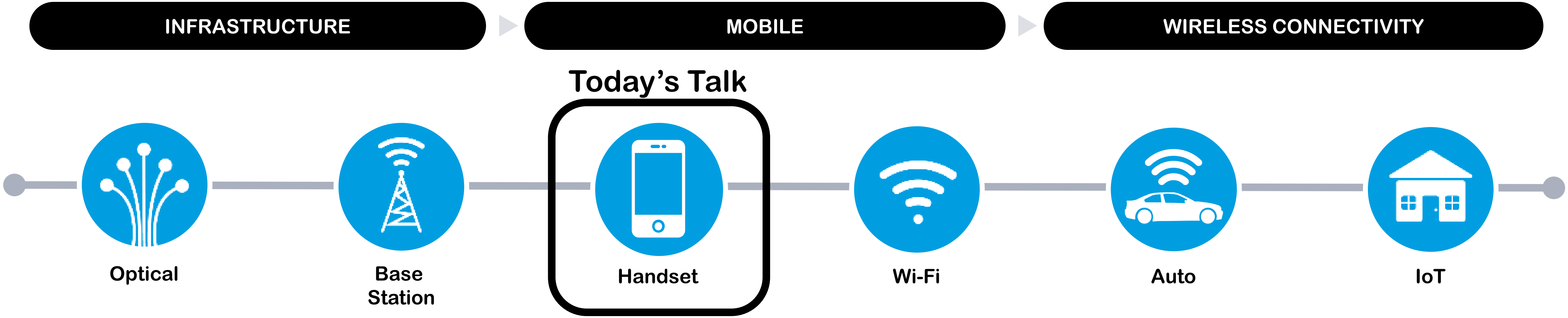
April 2019

Presenter: Ben Thomas

Today’s Agenda

1. 5G and its Evolving Market
2. 5G in the Mobile Handset
3. Front End Module Design Impacts

Qorvo: Delivers 5G RF Solutions—End to End



- Enabling 5G base station deployments today, helping develop 5G mobile devices of tomorrow
- Supporting robust 5G design activity for all 5G bands, Sub-6 GHz and mmW applications
- Playing a key role in defining 5G architectures with Qorvo's envelope tracking, antenna tuning, filters and phase array technology

Momentum for Full Scale 5G Handset Rollout

2019 | 2020 | 2021 | 2022

5G NR Limited Production
NSA and SA(China)
Release 15 Focused

5G NR Full Rollout
All Regions
Release 16 Focused

Radio Specifications

NSA: LTE Anchor, 5G NR Dual Connect
5G NR: Sub 6 GHz, mmW

New 5G NR Modules, 5G Re-farming,
NSA, Selective SA Rollout (China)

5G SA Upgrades
5G NR Re-farming Expansion

Device Rollout

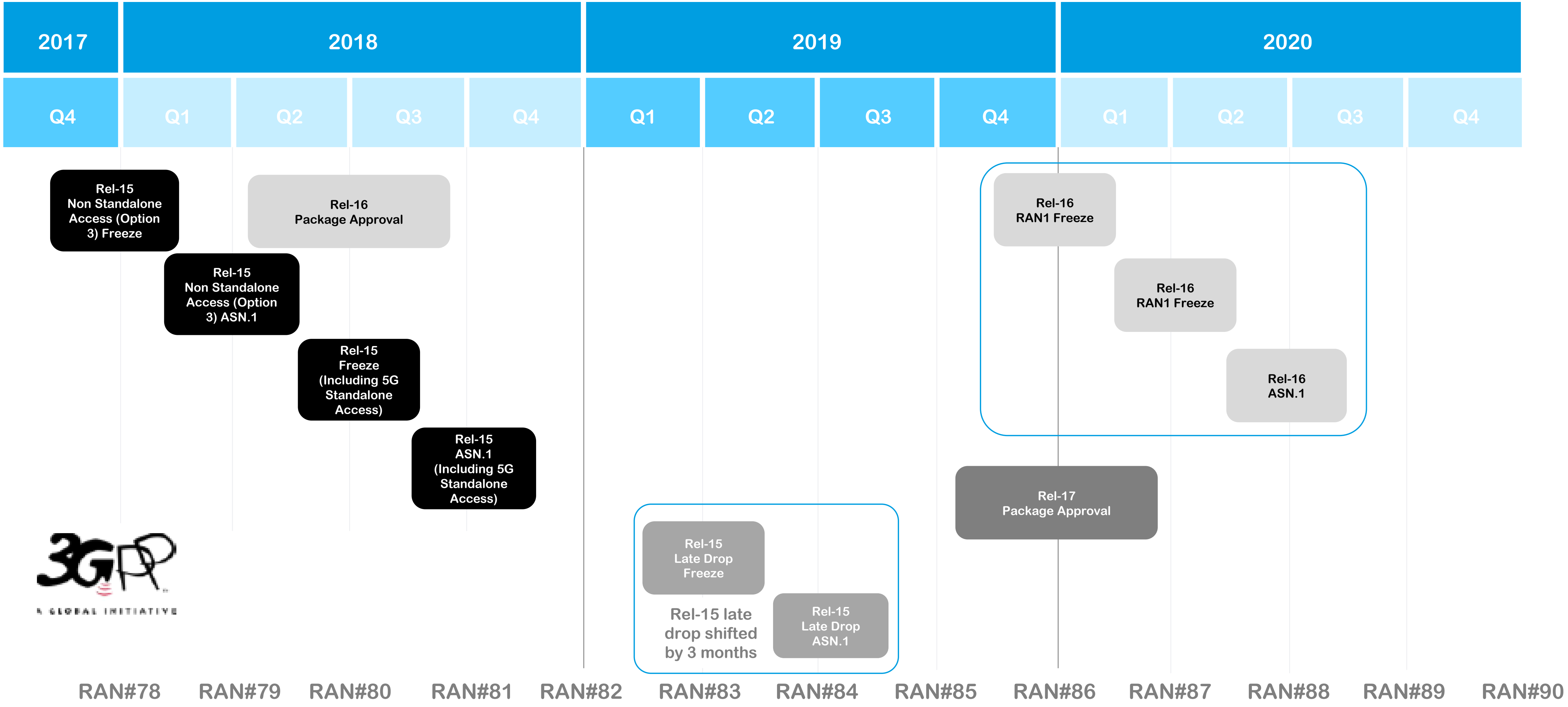
Flagship trials

Flagship models

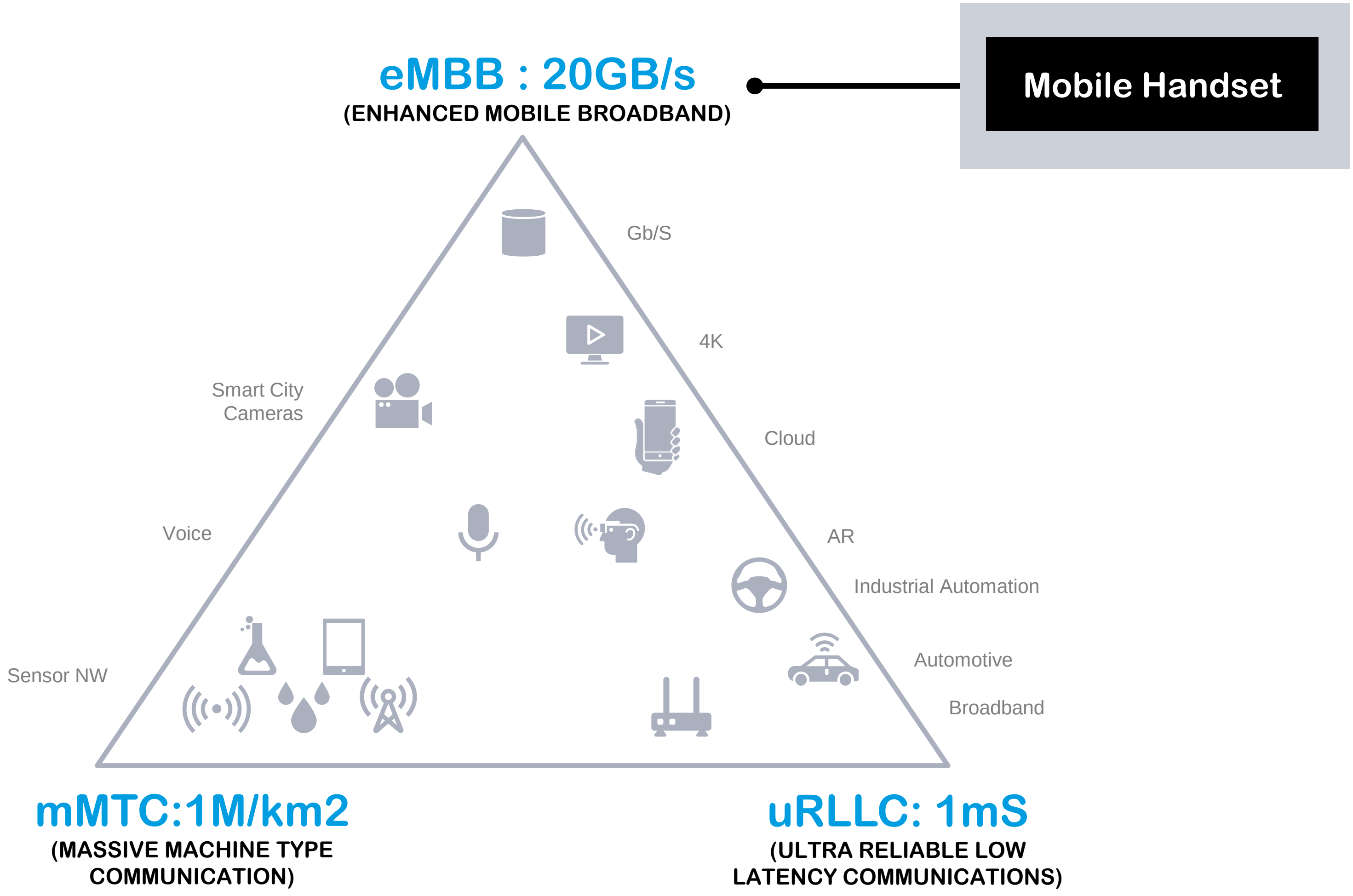
Mid-tier expansion

3GPP Release Schedule Through Rel. 16

Release 15 finally finishing up, Release 16 close behind



5G: 1 Standard, Multiple Markets



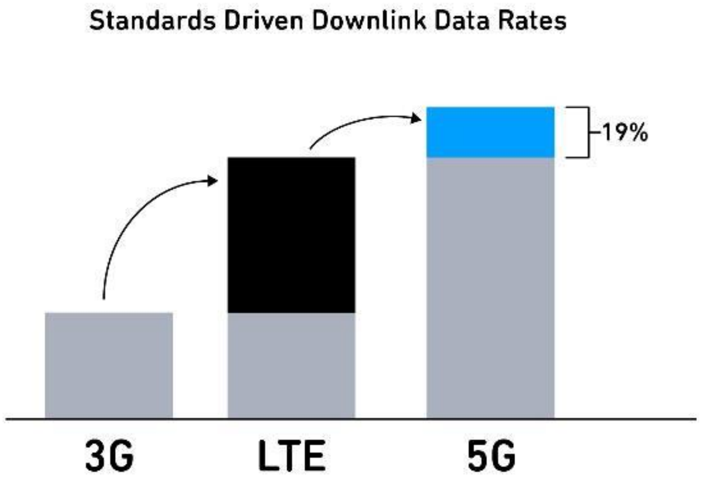
- First to 5G w/ Rel. 15 NSA
- Small data rate improvement
- Big BW improvement
- New bands and RF content
- All driving many, new RF challenges

Source: ITU-R IMT 2020 requirements

5G Promises of Data Improvement

5G NR downlink compared to 4G LTE

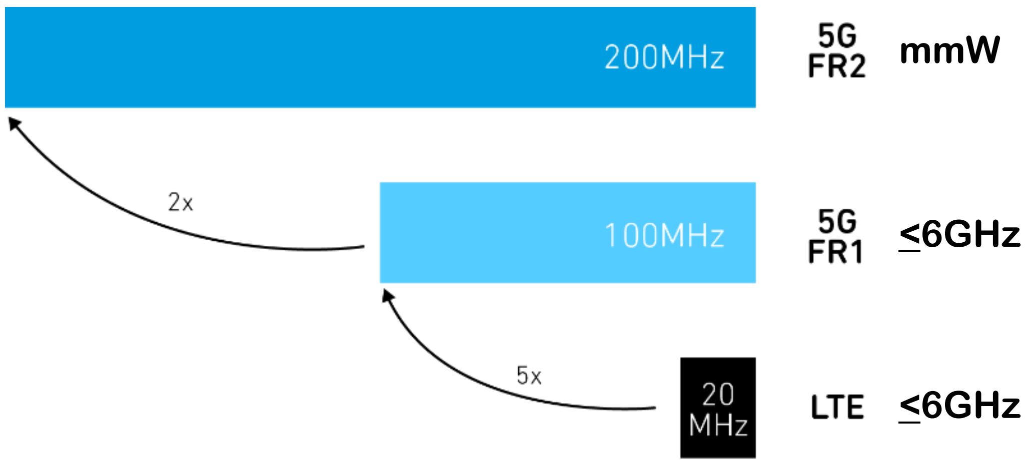
Nominal benefit from 5G standard



FR1 Example: DL 100 MHz FDD channel, strong signal, 4x4 MIMO, 256QAM, variable SCS

- LTE DL max 1.96 Gbps (5CC CA, 1CC=20MHz) = Baseline
- 5G NR DL max is 2.34 Gbps (273 RB, 30 kHz SCS) = 19.4% gain

Big increase due to bandwidth



FR1 Example: DL TDD 4x4 MIMO, 256QAM, 30 kHz SCS

- 20 MHz channel max is 0.281 Gbps (51 RB) = Baseline
- 100 MHz channel max is 1.50 Gbps (273 RB) = 5.3x gain

FR2 Example: DL TDD 4x4 MIMO (4 layers), 256QAM, 120 kHz SCS

- 100 MHz channel max is 1.50 Gbps (66 RB) = Baseline
- 200 MHz channel max is 3.0 Gbps (132 RB) = 2x gain
- 400 MHz channel max is 6.0 Gbps (264 RB) = 4x gain

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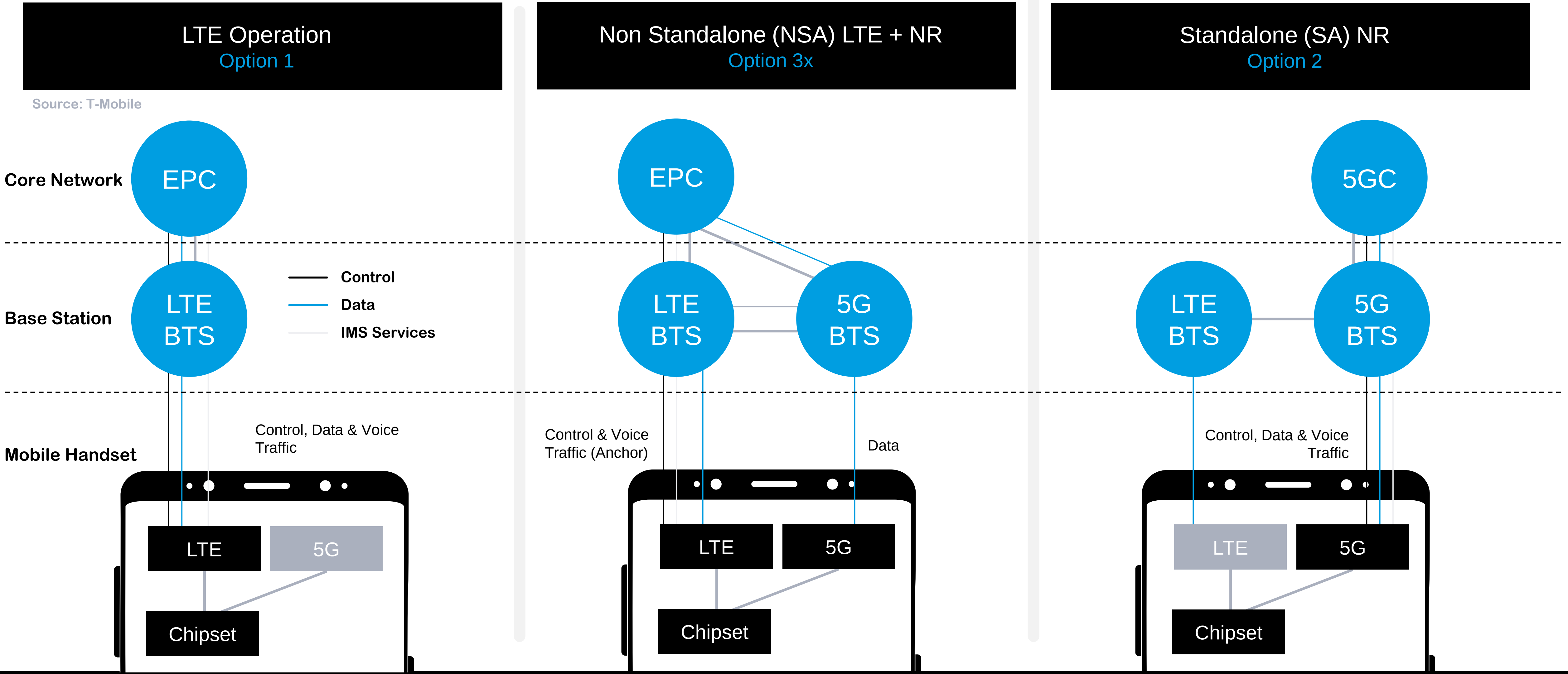
Progressive Transition of 5G Deployment

Mobile Operator Impact: Medium Large
Handset RF Impact: Large Small



Key RF Challenges for 5G Handsets

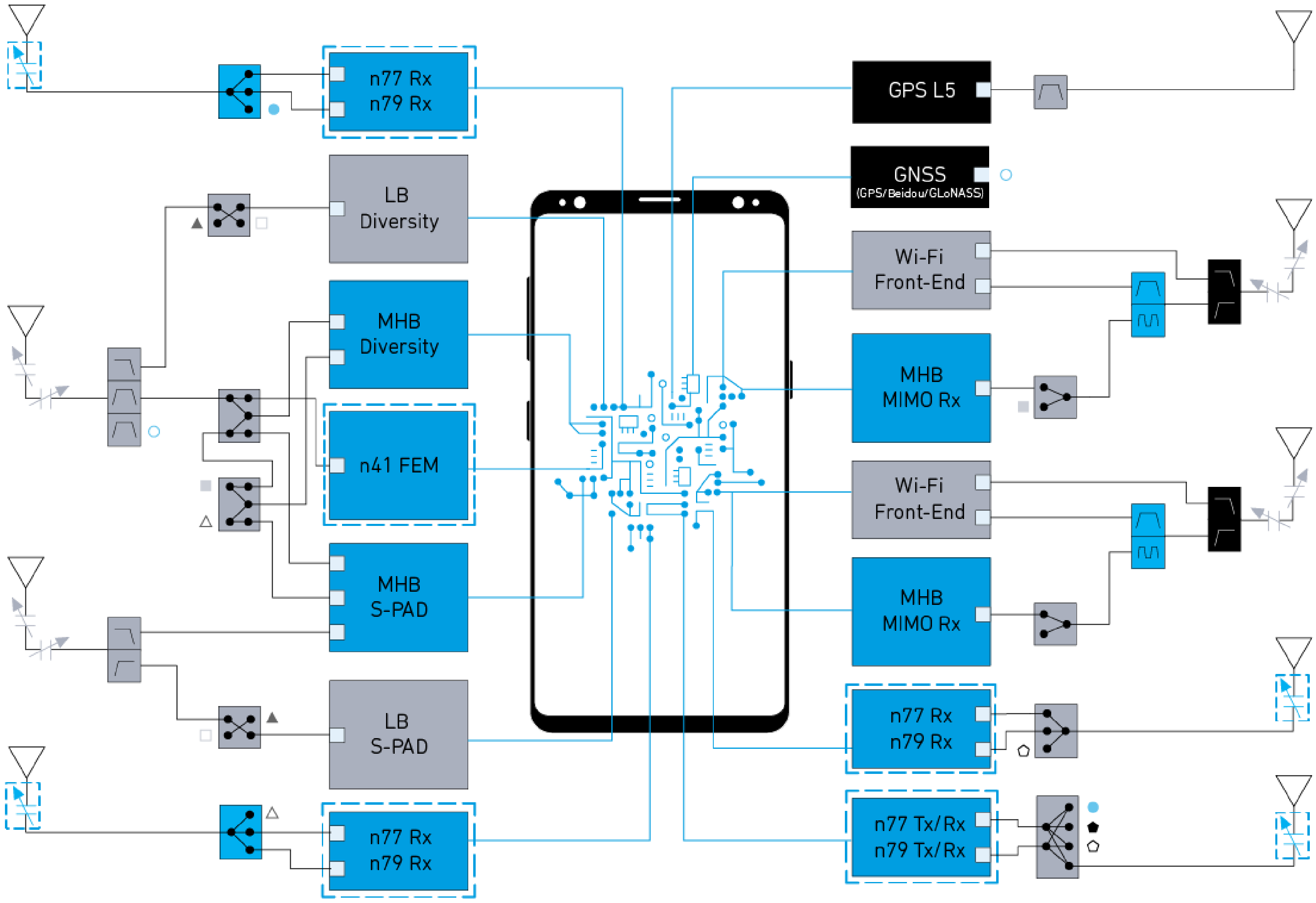
Included in 3GPP Release 15 and 16 specifications

	CHALLENGE
Bands	New bands with unprecedented bandwidth; accelerated LTE band re-farming
Modes	New waveforms with variable sub carrier spacing and dynamic power reduction + LTE
Signal Routing	LTE Anchor + 5G NR = Dual uplink connection
Switching Speed	Standard requires reduced latency and SRS

SOLUTION

- n77/n78 and n79 FE and DRx modules
- Upgraded LTE FEMs and DRx modules for 5G NR
- High performance Antennaplexers
- Antenna tuning and routing

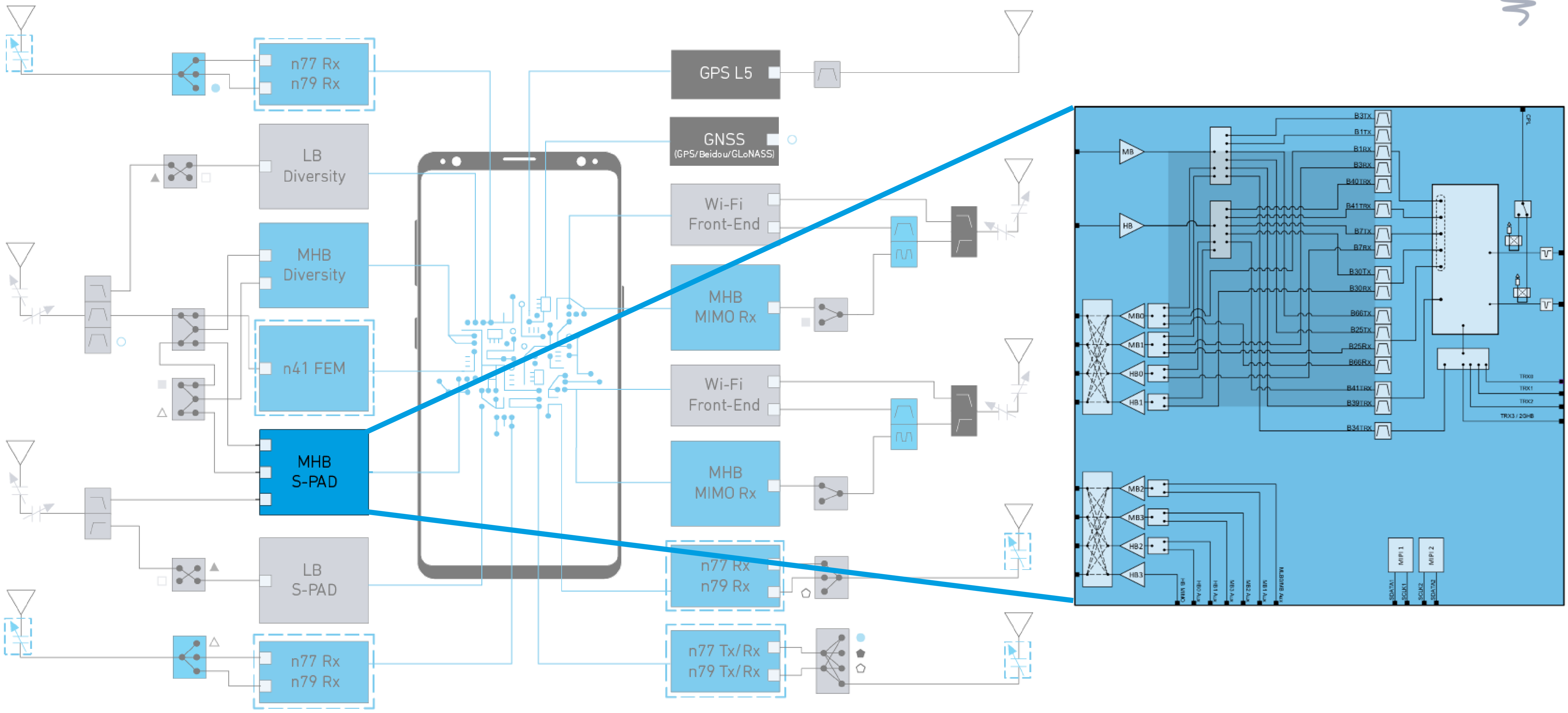
Impact of 5G on Global Handsets



5G's RF Impact

- None
- Low
- High
- New for 5G

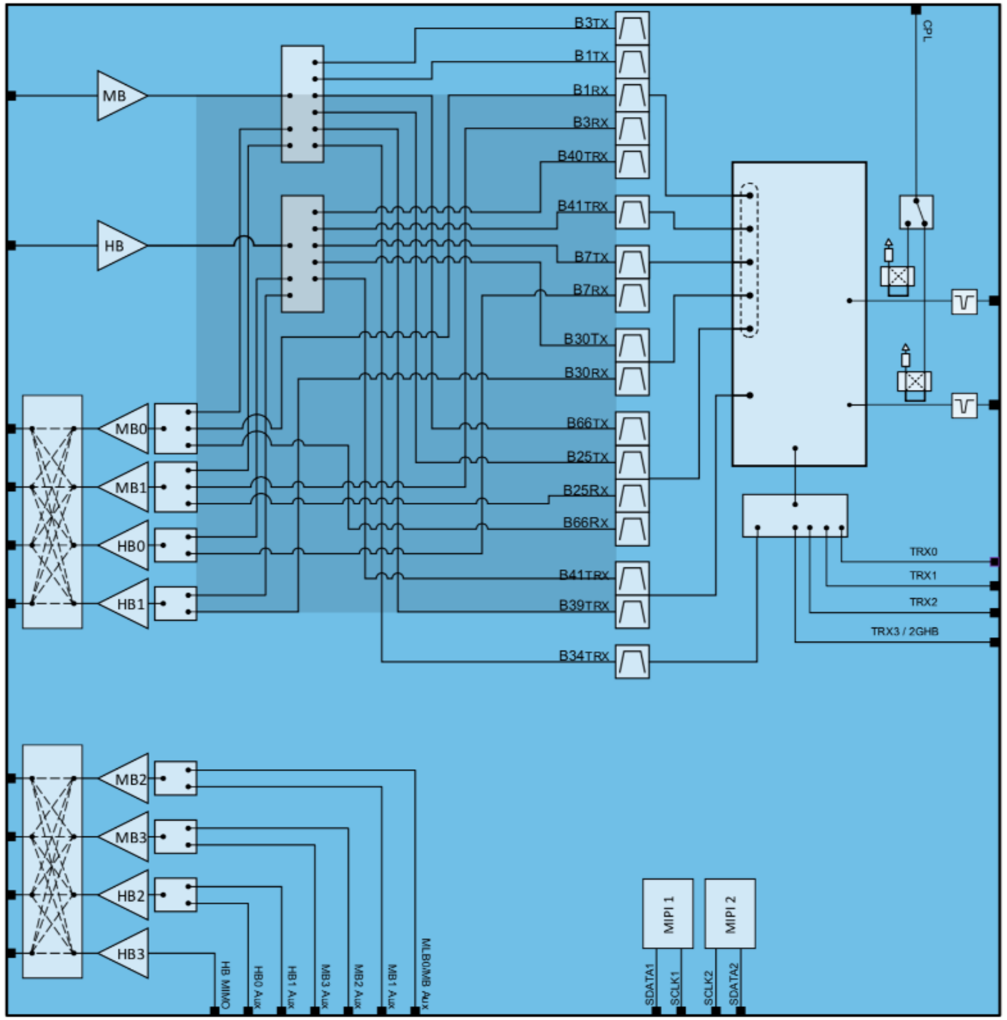
Deep Dive: 5G Impact on Mid/High Band S-PAD



Mid/High Band Feature/Scope Over Time

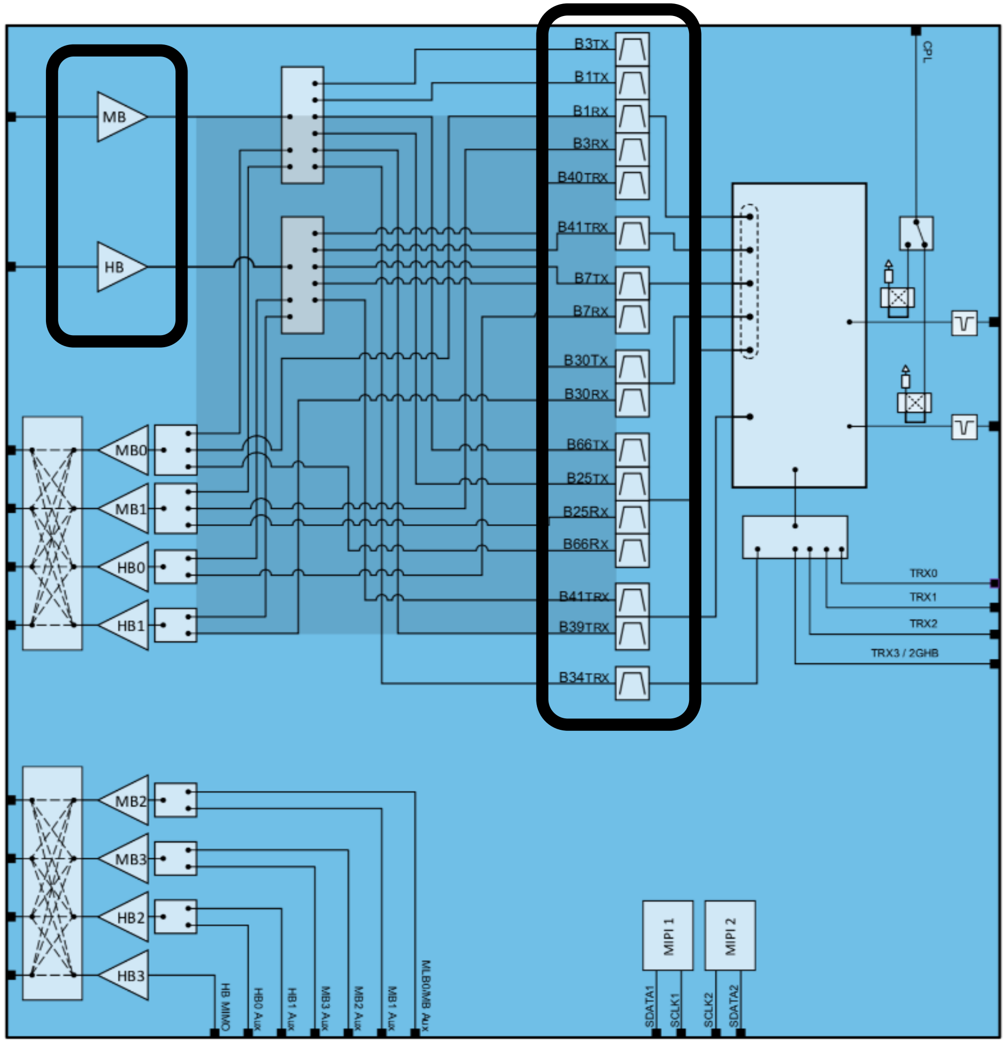
			LTE Advanced	5G
Features	**2015**	**2017**	**2019**	**2020**
Numbers of RF paths	14	22	>100	>300
Number of filter-band paths	7	12	18	19
Maximum of filters combined at one node for Carrier Aggregation	2	6	8	15
Critical LTE Isolation specs	2	36	51	74
Max bandwidth of transmit signal	20MHz	40MHz	60MHz	100MHz
PA Max Frac Bandwidth	15.6%	14.6%	16.9%	16.9%
Power Class 2 (3dB higher power)	No	No	Yes	Yes
Antenna Switch Integration	No	Yes	Yes	Yes
LNA integration	No	No	Yes	Yes
Envelope Tracking or Average Power Tracking (ET or APT)	APT	ET	ET	ET & APT
Number of filter-band paths	7	12	18	19
Incremental Size Change	Baseline	+25%	+50%	-35%

5G MB/HB S-PAD Example Architecture

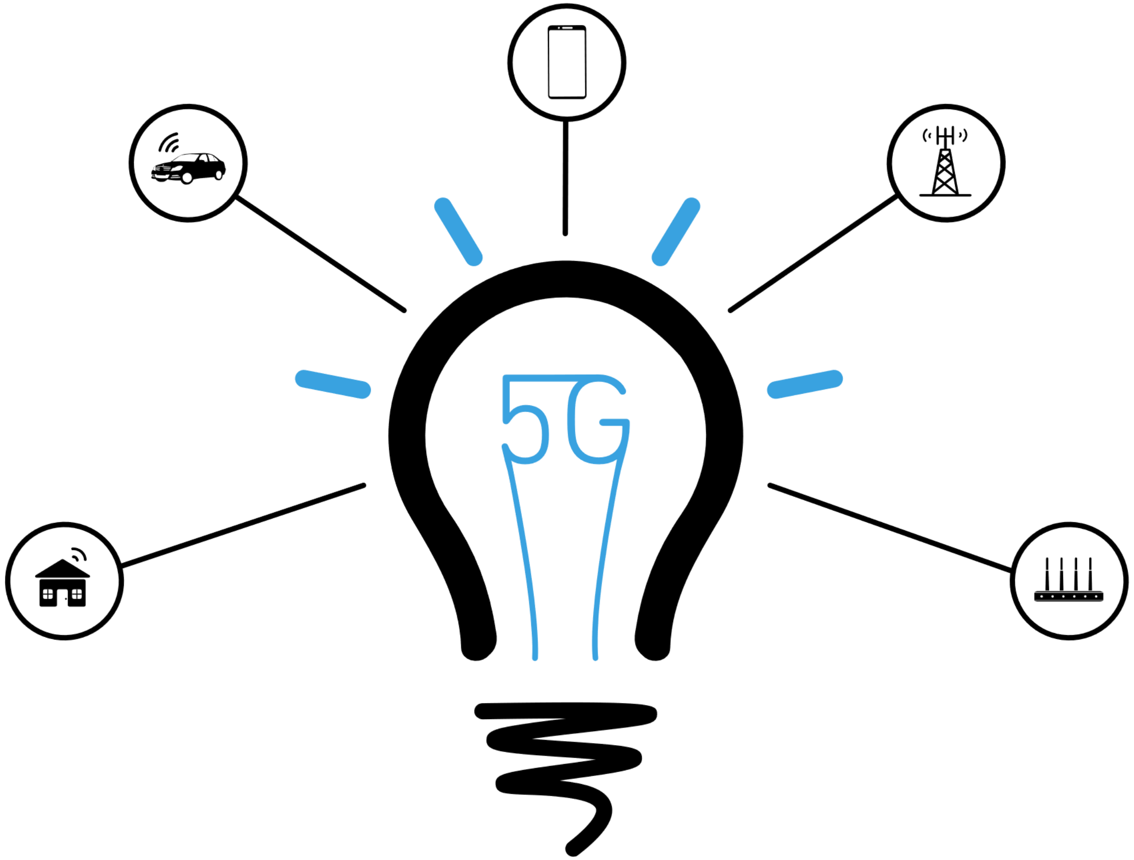


- Construction:
  - 25 Die in 4 Semiconductor Processes:
    - GaAs HBT, SOI, Bulk CMOS, BAW
  - 10 Layer laminate
  - MicroShield™ self-shielding
- Functions:
  - Mid Band and High Band Power Amplifiers (PAs) for Transmit (Tx)
  - Switch/Filtering for Carrier Aggregation Modes
  - Low Noise Amplifiers (LNA) for Receive (Rx)
  - Antenna Switch for 2 Antenna connections
  - Dual MIPI Controllers

5G Impact: 2 Key Areas Requiring Upgrades



- Power Amplifiers (PAs):
  - More Power
  - More Linearity
  - Many more points in between
- Filters:
  - Increased Carrier Aggregation (CA) Cases
  - While handling this increased Tx Power



5G: Power Amplifier Impacts

5G Waveforms: Significant Impact on the UL

Significant impact on the UL

- 4G and 5G both based on OFDM:
  - 4G LTE used SCFDMA in the and OFDMA in the DL
  - 5G NR uses both CP-OFDM and DFT-s-OFDM in the UL and keeps CP-OFDM in the DL
    - DFT-s-OFDM is the same as LTE's SCFDMA
    - CP-OFDM is the same as LTE's OFDMA
- Why use (CP-) OFDM?
  - CP-OFDM ranks best on the performance indicators that matter most in 5G – compatibility with multi-antenna technologies, high spectral efficiency, and low implementation complexity.
- CP-OFDM is well-controlled in the time domain
  - Important for latency critical applications and TDD deployments
  - More robust to phase noise and Doppler than other waveforms
- However, OFDM has two drawbacks: high PAR on the UL and transceiver complexity
  - Thus why DFT-s-OFDM is used for coverage-limited scenarios

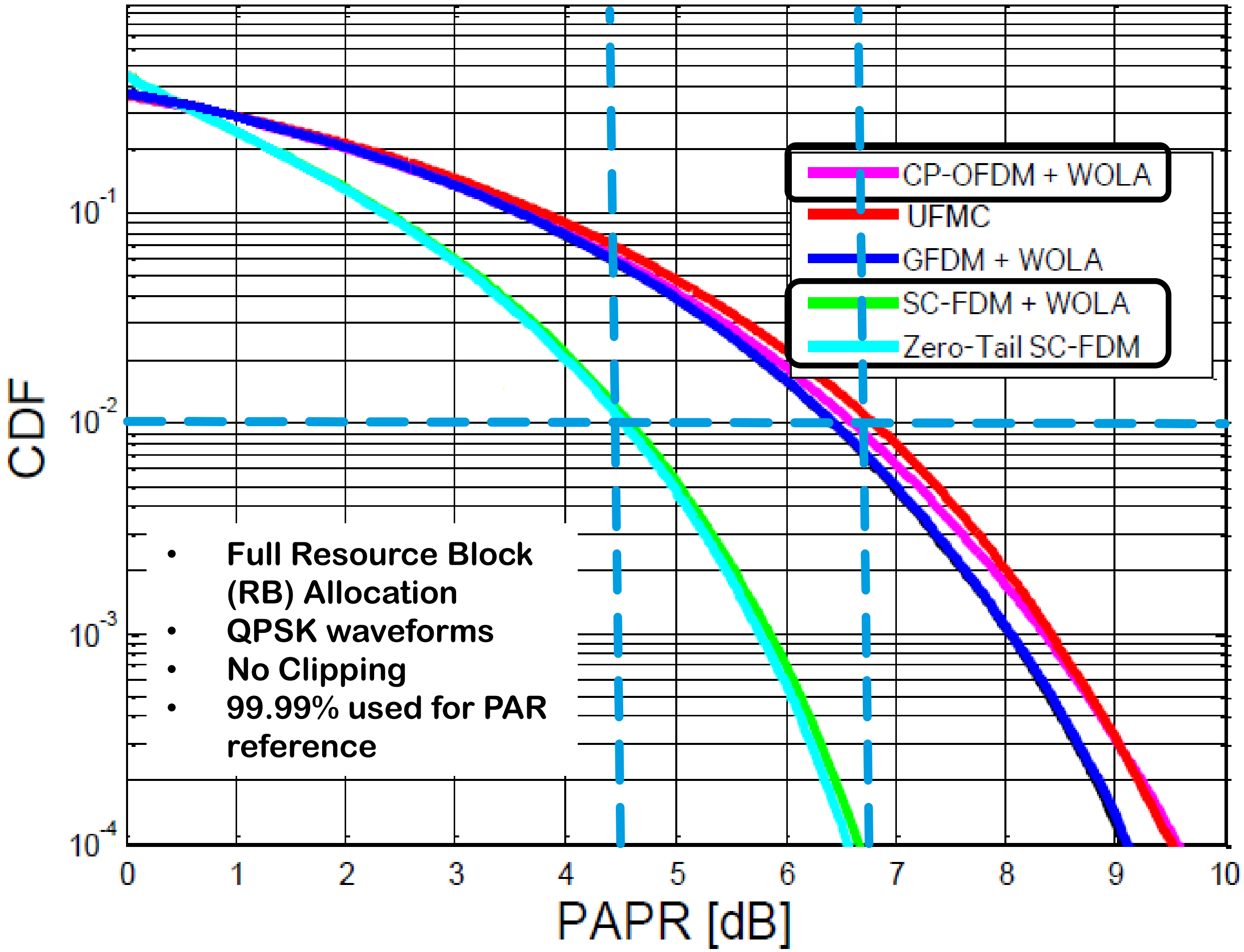
Evaluation of CP-OFDM

Performance Indicators	Goodness of Fit	DL Req.	UL Req.
Spectral efficiency	High	High	High
MIMO Compatibility	High	Very High	Very High
Time localization	High	High	High
Transceiver complexity	Low	Very High	High
Flexibility/Scalability	High	High	High
Robustness to frequency selective channel	High	High	High
Robustness to time selective channel	Medium	High	High
Robustness to phase noise	Medium	High	High
Robustness to synchronization errors	Medium	Medium	Medium
PAPR	Medium (can be reduced)	Low	High
Frequency Localization	Low (can be enhanced)	Medium	High

5G Waveforms: Peak to Average Ratio (PAR)

Representative waveforms for comparison of CP-OFDM and DFT-s-OFDM

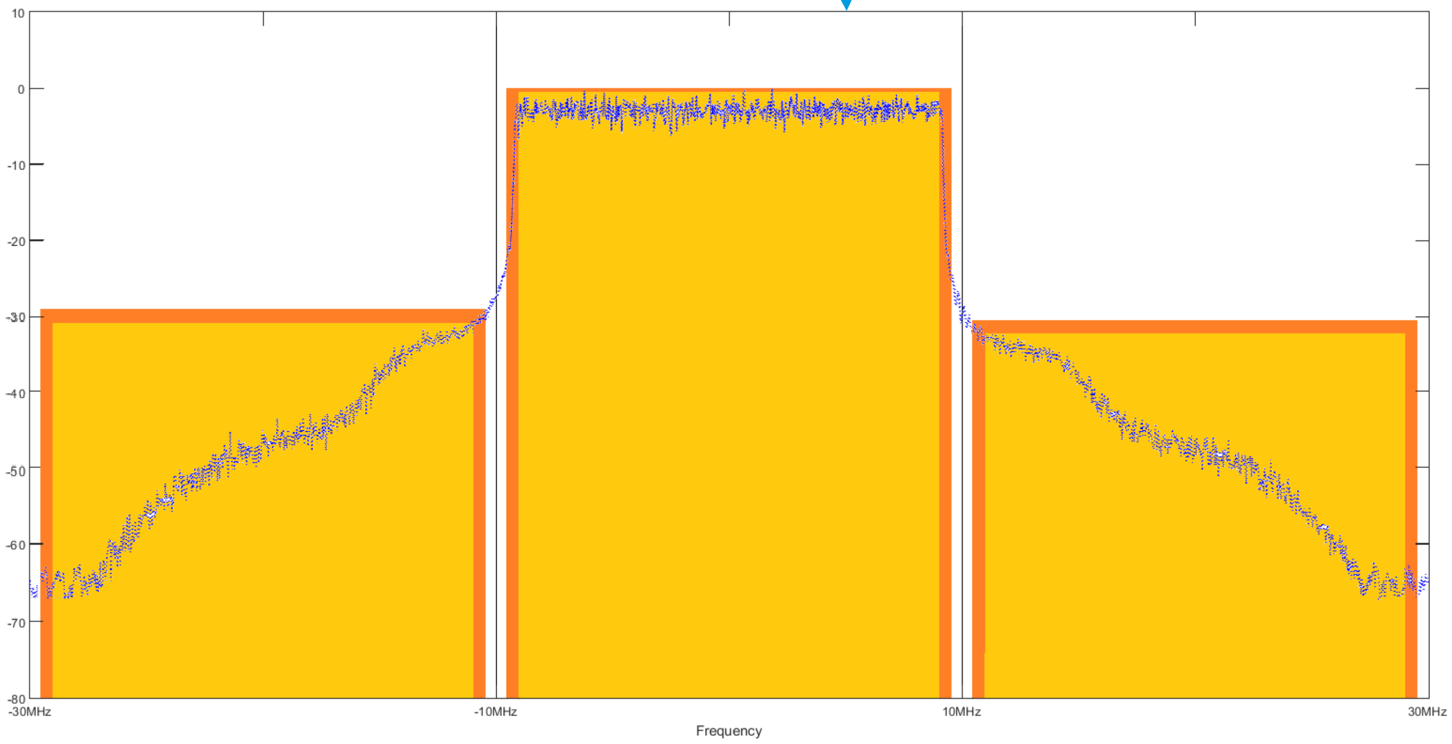
- CP-OFDM waveform has 2-2.5dB higher PAR than SC-FDMA/DFT-s-OFDM waveforms
- Further, as the complexity of the IQ modulation increases the PAR also increases
  - QPSK→16QAM→64QAM→256QAM
- Result: PA designed to handle such large swings of Power (and underlying voltage) at the collector; Robustness needed



ACLR measurement has subtle changes in 5G

- **EUTRA ACLR is changed from LTE:**
  - **Same spec (-30dBc), but…**
  - **Different measurement BWs in NR vs. LTE**
    - Integrated channel power is not much different
    - Integrated adj. channel power is a little higher
    - End result: 5G ACLR is tougher
- **5G UTRA ACLR is very similar to LTE**
  - **Same specs (-33, -36)**
  - **Difference in int. BW for channel power**
  - **5G waveform occupies more BW**
- **Results: 5G UTRA should be slightly more difficult than 4G UTRA**

EUTRA Channel bandwidth / ACLR measurement bandwidth												
	1.4MHz	3MHz	5 MHz	10 MHz	15 MHz	20 MHz	25 MHz	40 MHz	50 MHz	60 MHz	80 MHz	100 MHz
4G LTE ACLR measurement bandwidth	1.08	2.7	4.5	9	13.5	18						
5G NR ACLR measurement bandwidth			4.515	9.375	14.235	19.095	23.955	38.895	48.615	58.35	78.15	98.31



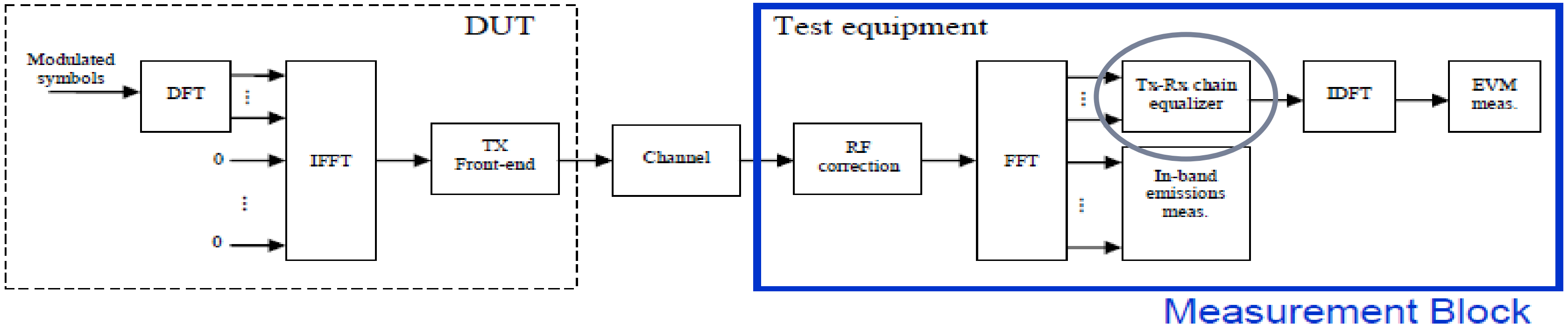
LTE and NR EVM

EVM in LTE/NR is different than other communication standards

- **NR EVM is a lot like LTE EVM:**
  - **EVM calculated per resource block**
  - **EVM includes a frequency domain equalizer (after FFT)**

3GPP 5G EVM Specification:

Parameter	Unit	Average EVM Level
Pi/2-BPSK [or BPSK]	%	[25]
[BPSK or] QPSK	%	17.5
16 QAM	%	12.5
64 QAM	%	8
256 QAM	%	3.5



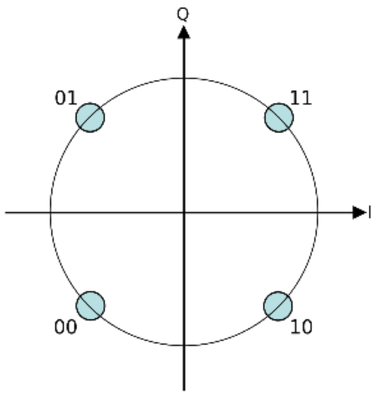
$$EVM = \sqrt{\frac{\sum_{v \in T_m} \left| z'(v) - i(v) \right|^2}{\left| T_m \right| \cdot P_0}}$$ for allocated Resource Block

$z'(v)$ is modified signal under test

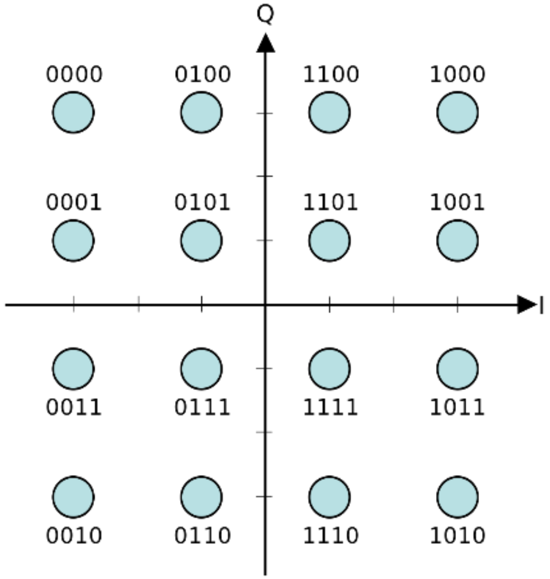
$i(v)$ is the ideal signal reconstructed by the measurement equipment

New 5G features: Higher Order UL Modulations

(each sub-carrier is modulated using these schemes)

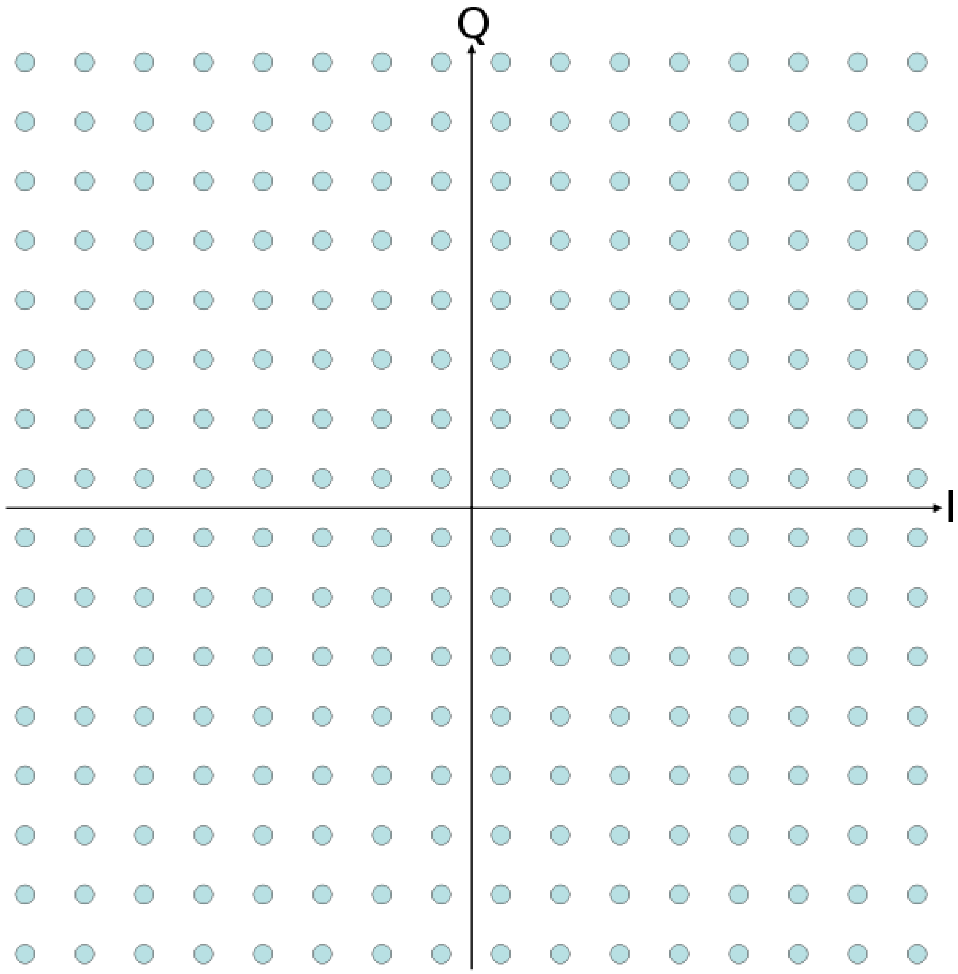


QPSK
(4 QAM)
2bit / symbol



16 QAM
(4 bit/symbol)

...
32 QAM
64 QAM



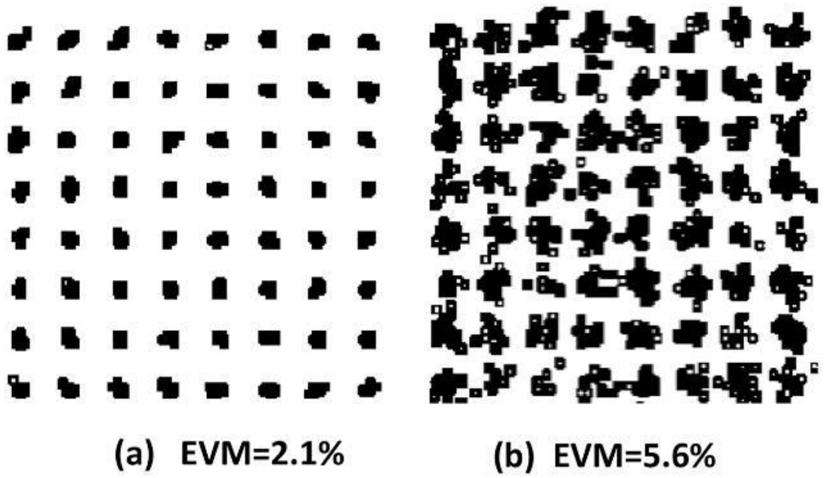
256 QAM: 8 bit/symbol

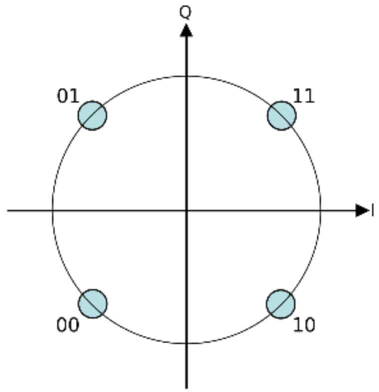
More to come: 1024 QAM?

Focus on EVM for Higher Order Constellations

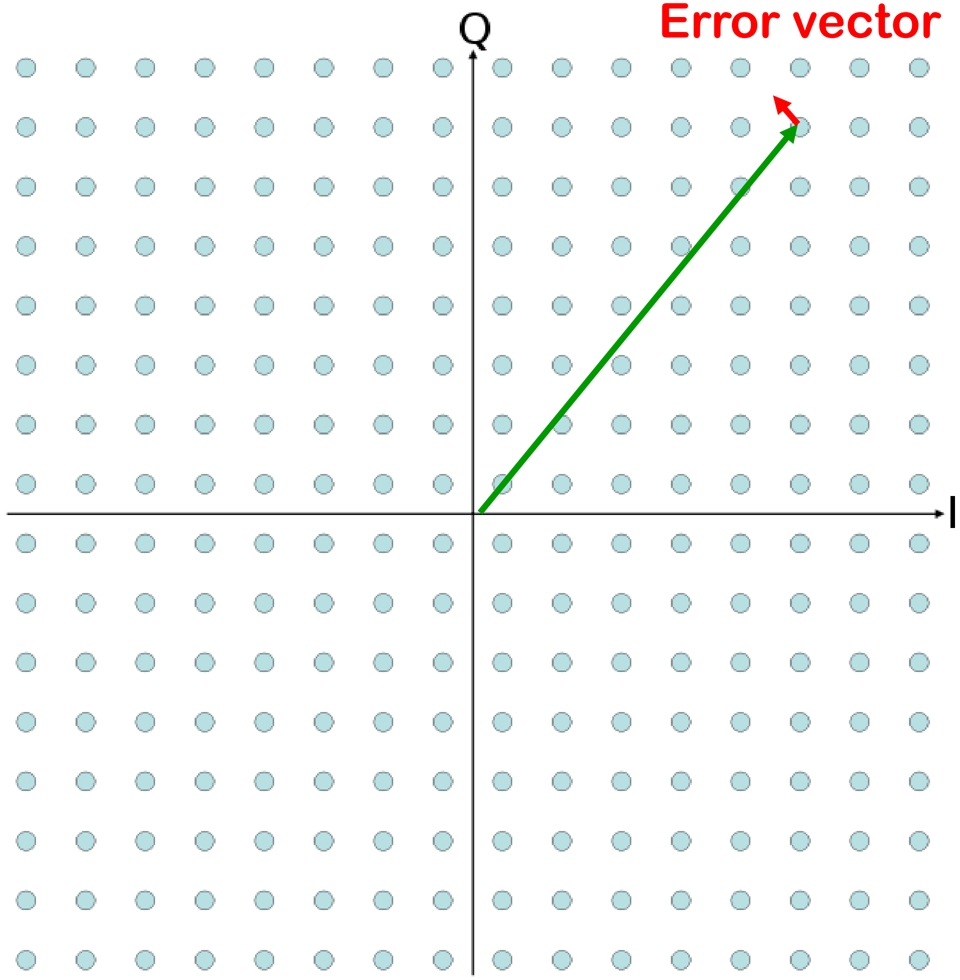
(each sub-carrier is modulated using these schemes)

Example: 64 QAM:





QPSK
(4 QAM)
2bit / symbol



Very little EVM can be accepted at the Receiver side before bits are confused!

Result: For both 64, and *especially* 256 QAM UL EVM is key spec !

Multiple 5G PA Operating Points to Consider

Increased complexity with variables of waveform, modulation, RB allocation

Table 6.2.2-1 Maximum power reduction (MPR) for power class 3

Modulation	MPR (dB)			Dominant Factor
	Edge RB allocations	Outer RB allocations	Inner RB allocations	
DFT-s-OFDM PI/2 BPSK	≤ 3.5[1]	≤ 1.2[1]	≤ 0.2[1]	ACLR
	0.5[2]	0.5[2]	0[2]	
DFT-s-OFDM QPSK	≤ 1		0	
DFT-s-OFDM 16 QAM	≤ 2		≤ 1	ACLR & EVM
DFT-s-OFDM 64 QAM	≤ 2.5			EVM
DFT-s-OFDM 256 QAM	4.5			
CP-OFDM QPSK	≤ 3		≤ 1.5	ACLR
CP-OFDM 16 QAM	≤ 3		≤ 2	ACLR & EVM
CP-OFDM 64 QAM	≤ 3.5			EVM
CP-OFDM 256 QAM	≤ 6.5			

NOTE 1: Applicable for UE operating in TDD mode with PI/2 PBSK modulation and UE indicates support for UE capability [*powerBoosting-pi2BPSK*] and if the IE *powerBoostPi2BPSK* is set to 1 and 40% or less slots in radio frame are used for UL transmission for bands n40, n41, n77, n78 and n79. The reference power of 0 dB MPR is 26 dBm.

NOTE 2: Applicable for UE operating in FDD mode, or in TDD mode in bands other than n40, n41, n77, n78 and n79 and if the IE *powerBoostPi2BPSK* is set to 0 and if more than 40 % of slots in radio frame are used for UL transmission for bands n40, n41, n77, n78 and n79.

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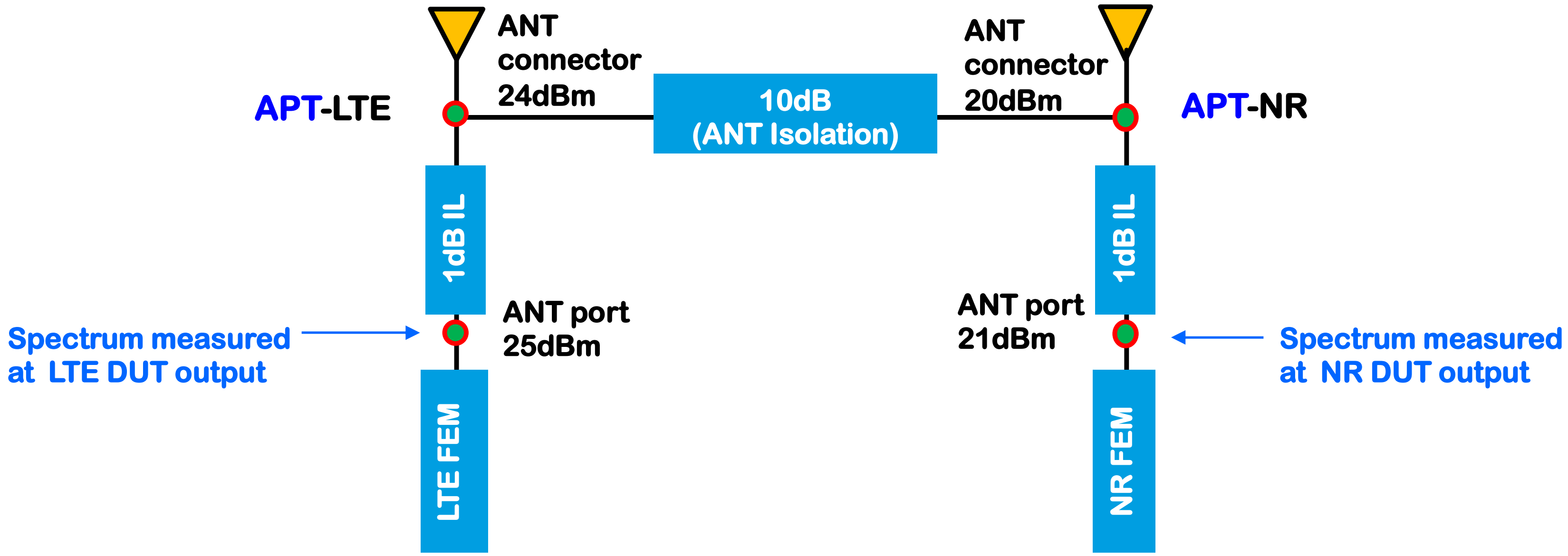
5G's NSA EN-DC Drives UL Challenges

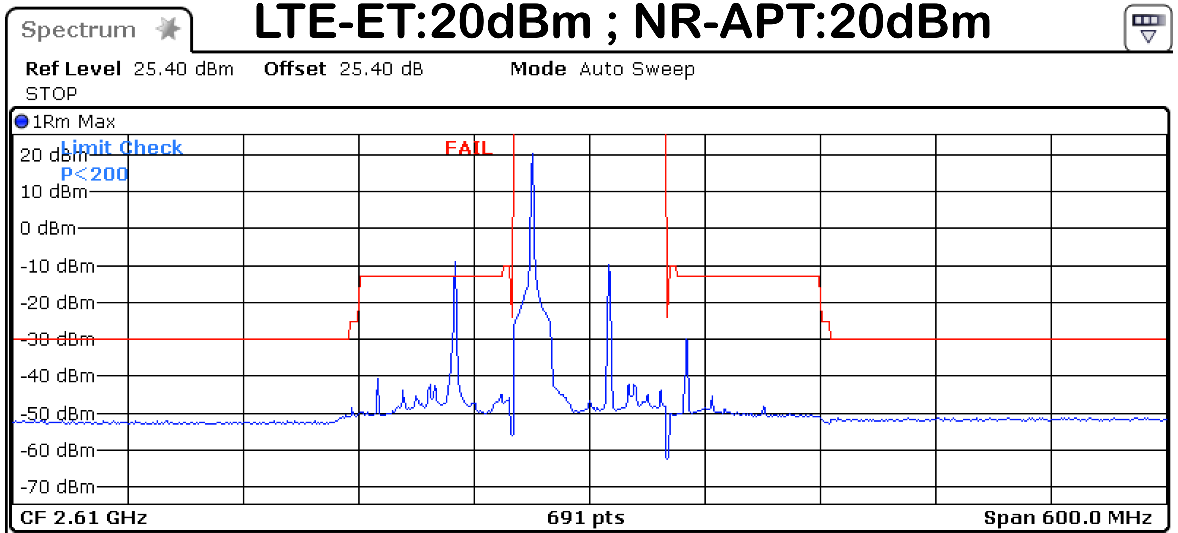
LTE's B1+B3 dual UL was never widely deployed

- EN-DC= EUTRA + NR – Dual Connection
  - LTE "control" anchor and NR "data" signal UL from the handset simultaneously
- 2 PAs transmitting at the same time, from antennas in near proximity!
- 2 Areas to watch: Total Power and rIM3 interference leading to OOB emissions



B41+n41: Difference in ET and APT

LTE-ET:20dBm ; NR-APT:20dBm

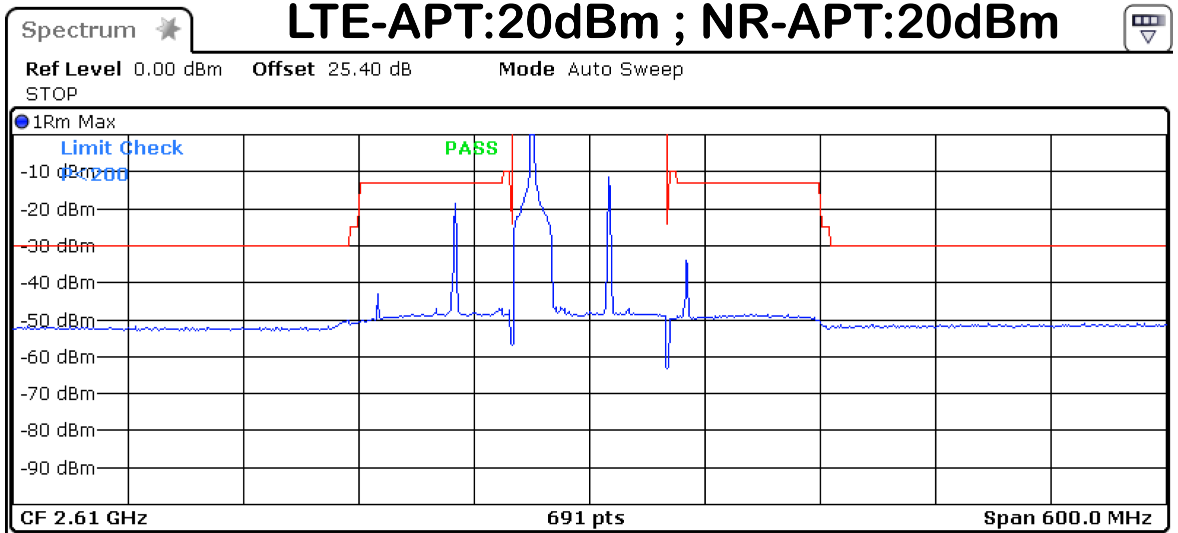


Spectrum Emission Mask — Standard: ENDC_80MHzSEMmask_Att10dB

Tx Power -41.89 dBm — Tx Bandwidth 3.840 MHz — RBW 1.000 MHz

Range Low	Range Up	RBW	Frequency	Power Abs	Power Rel	ΔLimit
-300.000 MHz	-125.000 MHz	1.000 MHz	2.48369 GHz	-50.57 dBm	-8.68 dB	-20.57 dB
-125.000 MHz	-120.000 MHz	1.000 MHz	2.48650 GHz	-48.57 dBm	-6.68 dB	-23.57 dB
-120.000 MHz	-45.000 MHz	1.000 MHz	2.54015 GHz*	-9.00 dBm*	32.88 dB*	4.00 dB*
-45.000 MHz	-41.000 MHz	1.000 MHz	2.56850 GHz	-45.62 dBm	-3.74 dB	-35.62 dB
-41.000 MHz	-40.000 MHz	30.000 kHz	2.56900 GHz	-55.84 dBm	-13.96 dB	-31.84 dB
40.000 MHz	41.000 MHz	30.000 kHz	2.65000 GHz	-62.32 dBm	-20.43 dB	-38.32 dB
41.000 MHz	45.000 MHz	1.000 MHz	2.65100 GHz	-49.90 dBm	-8.01 dB	-39.90 dB
45.000 MHz	120.000 MHz	1.000 MHz	2.65980 GHz	-29.85 dBm	12.04 dB	-16.85 dB
120.000 MHz	125.000 MHz	1.000 MHz	2.73000 GHz	-51.85 dBm	-9.96 dB	-26.85 dB
125.000 MHz	300.000 MHz	1.000 MHz	2.86255 GHz	-51.26 dBm	-9.37 dB	-21.26 dB

LTE-APT:20dBm ; NR-APT:20dBm

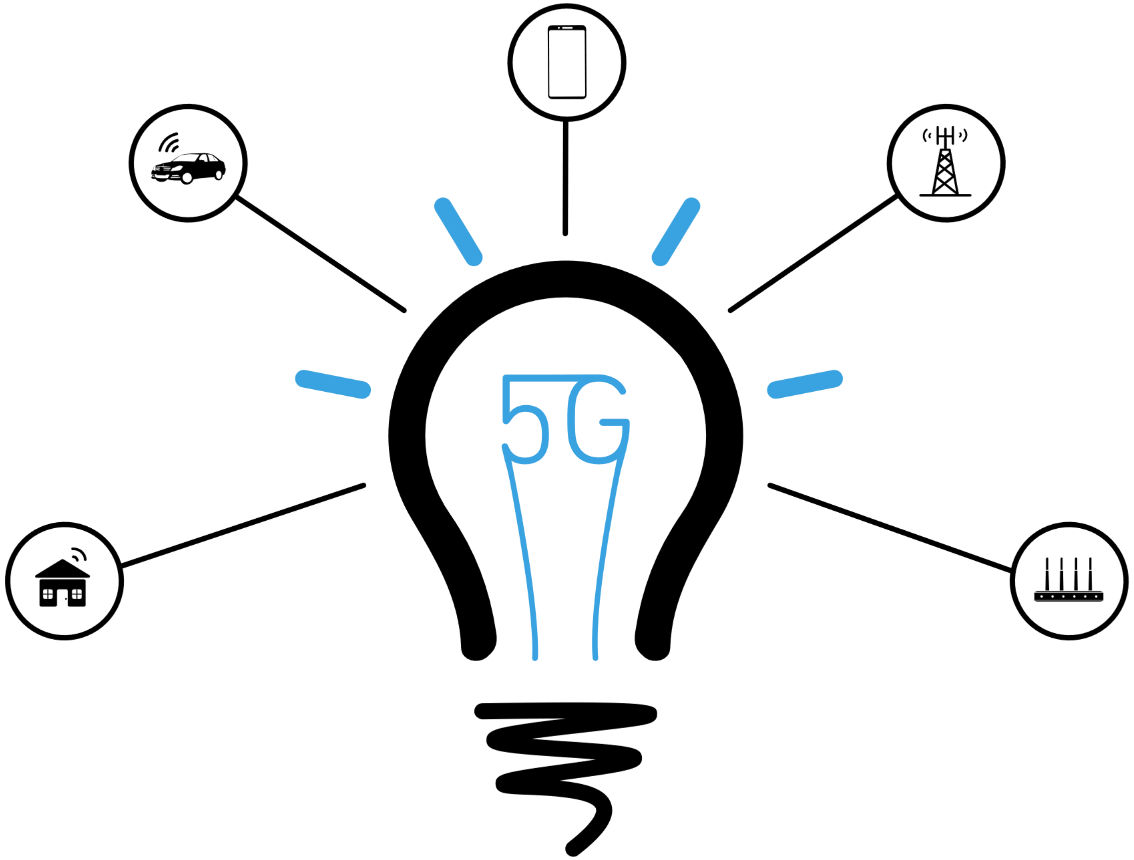


Spectrum Emission Mask — Standard: ENDC_80MHzSEMmask_Att10dB

Tx Power -42.54 dBm — Tx Bandwidth 3.840 MHz — RBW 1.000 MHz

Range Low	Range Up	RBW	Frequency	Power Abs	Power Rel	ΔLimit
-300.000 MHz	-125.000 MHz	1.000 MHz	2.48456 GHz	-50.37 dBm	-7.83 dB	-20.37 dB
-125.000 MHz	-120.000 MHz	1.000 MHz	2.48950 GHz	-51.06 dBm	-8.52 dB	-26.06 dB
-120.000 MHz	-45.000 MHz	1.000 MHz	2.54015 GHz	-18.69 dBm	23.85 dB	-5.69 dB
-45.000 MHz	-41.000 MHz	1.000 MHz	2.56850 GHz	-47.41 dBm	-4.87 dB	-37.41 dB
-41.000 MHz	-40.000 MHz	30.000 kHz	2.56900 GHz	-57.05 dBm	-14.51 dB	-33.05 dB
40.000 MHz	41.000 MHz	30.000 kHz	2.65000 GHz	-63.14 dBm	-20.60 dB	-39.14 dB
41.000 MHz	45.000 MHz	1.000 MHz	2.65100 GHz	-49.65 dBm	-7.11 dB	-39.65 dB
45.000 MHz	120.000 MHz	1.000 MHz	2.65980 GHz	-34.08 dBm	8.46 dB	-21.08 dB
120.000 MHz	125.000 MHz	1.000 MHz	2.73000 GHz	-51.34 dBm	-8.80 dB	-26.34 dB
125.000 MHz	300.000 MHz	1.000 MHz	2.89476 GHz	-51.05 dBm	-8.51 dB	-21.05 dB

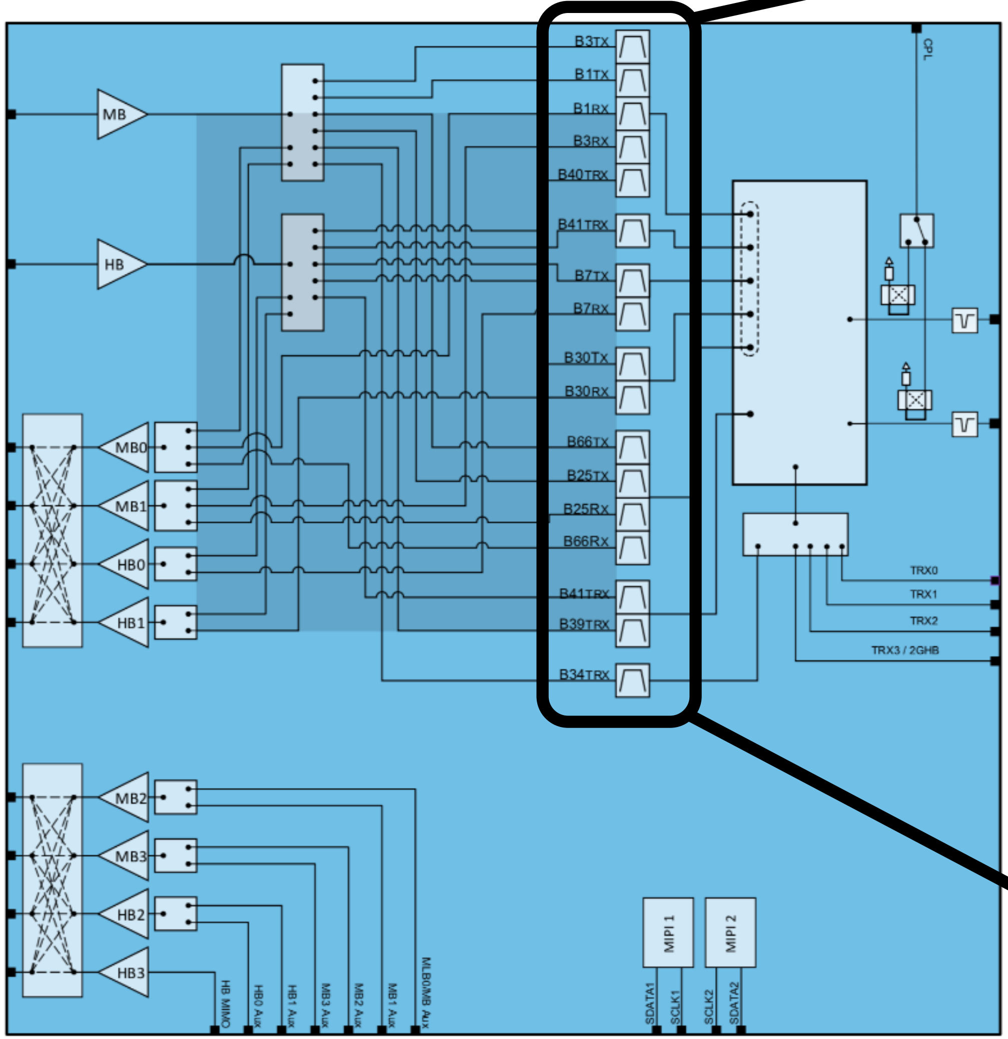
Results: Same PA that needs to operate in ET for single channel efficiency needs to be capable of APT in *certain* EN-DC combinations

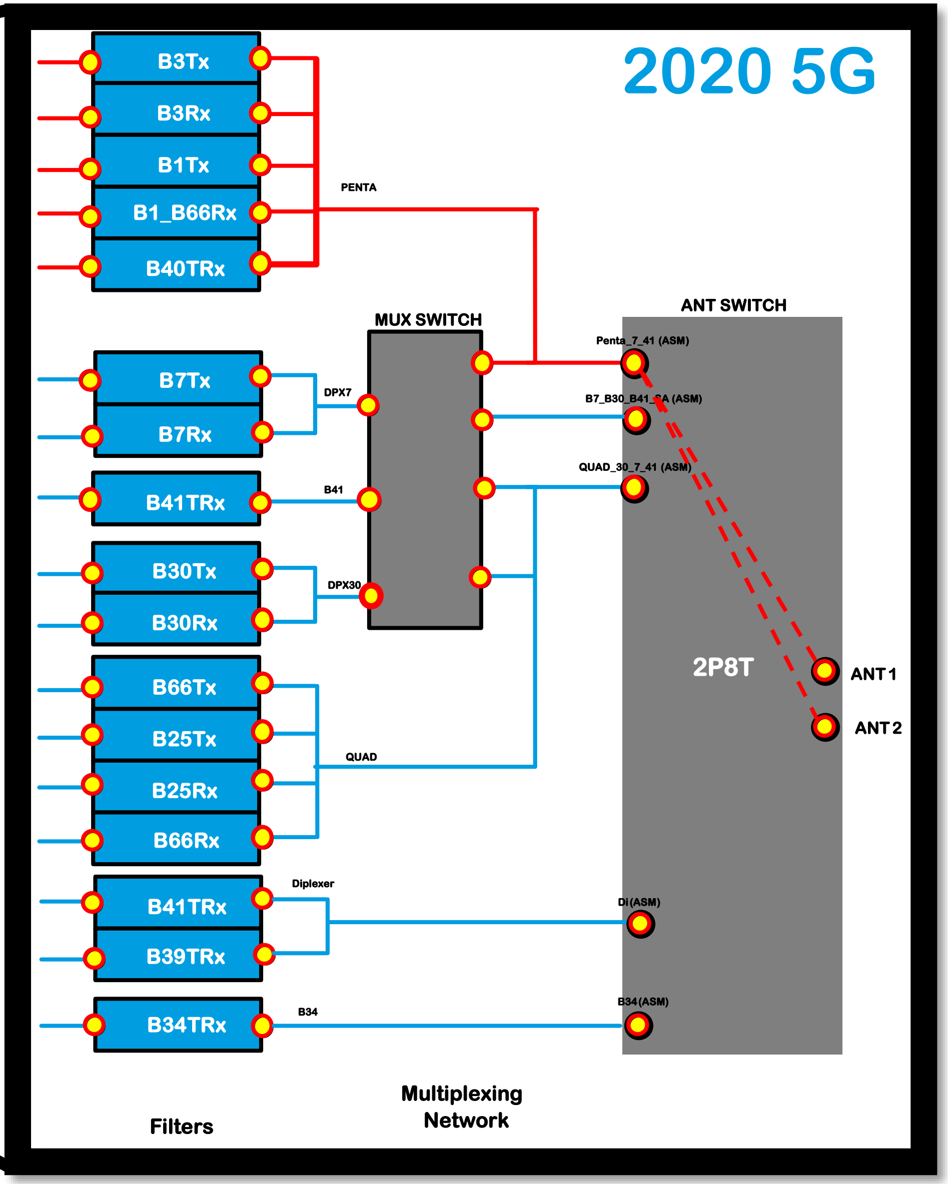


5G: Filter/Multiplexer Impacts

5G Impacts: Multiplexer Operation

Requires Massive Upgrade

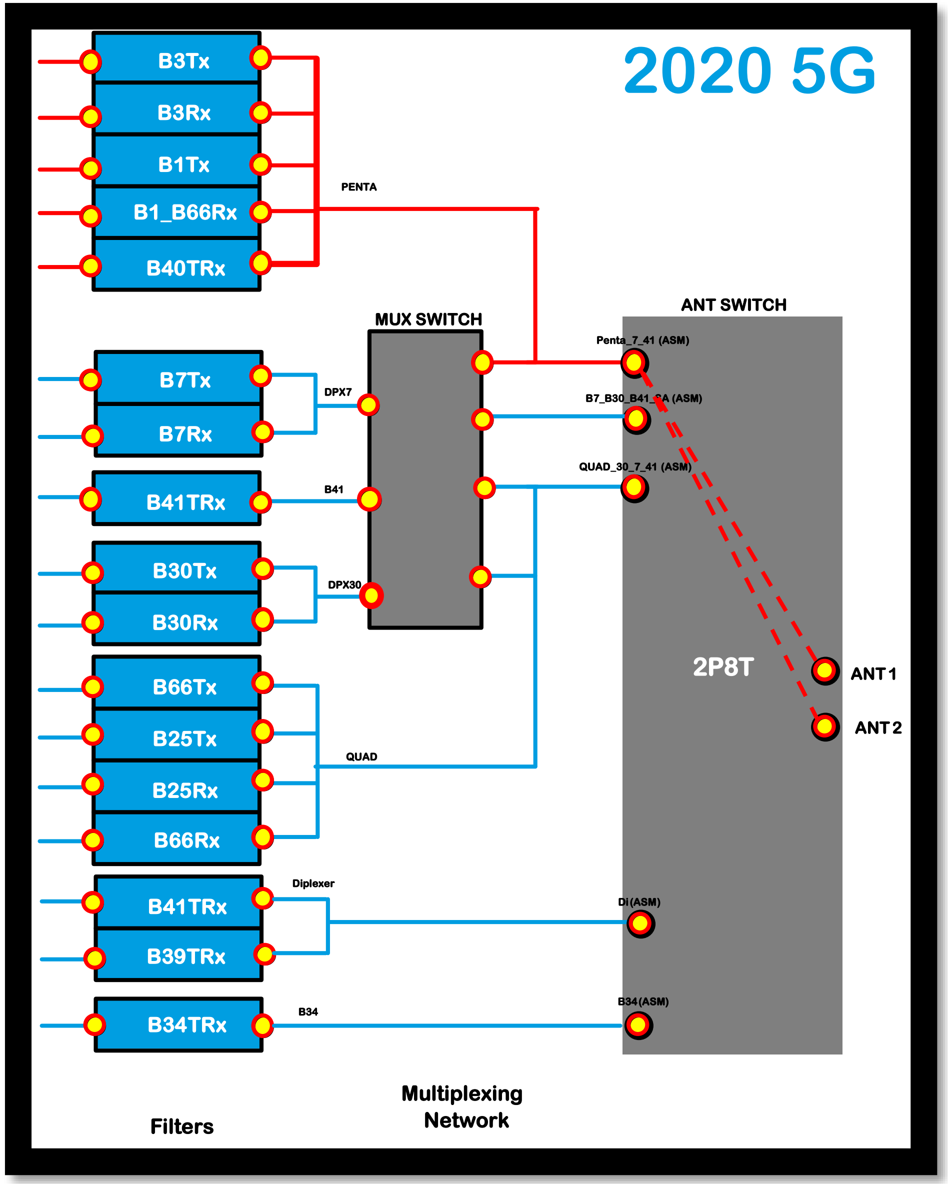




Multiplexer Functional Increase for 5G

Multiple filters combined to simultaneously send/receive signals:

- 2019 LTE: Switchable “9-plexer” with 3 modes:
  - Hexaplexer/MB mode
  - B7 mode: Hexaplexer+B7 (Octaplexer)
  - B38TRx/B41N mode: Hexaplexer+B38TRx/B41N (Septaplexer)
- 2020 5G: Switchable “Mux14” with 10 modes:
  - Pentaplexer Standalone: B1RX/TX + B3RX/TX + B40TRX
  - Pentaplexer + B7 Duplexer or B41 TRx
  - Quadplexer Standalone: B25RX/TX + B66RX/TX
  - Quadplexer + B7 Duplexer or B41TRx or B30
  - Standalone: B7 or B30 or B41TRx

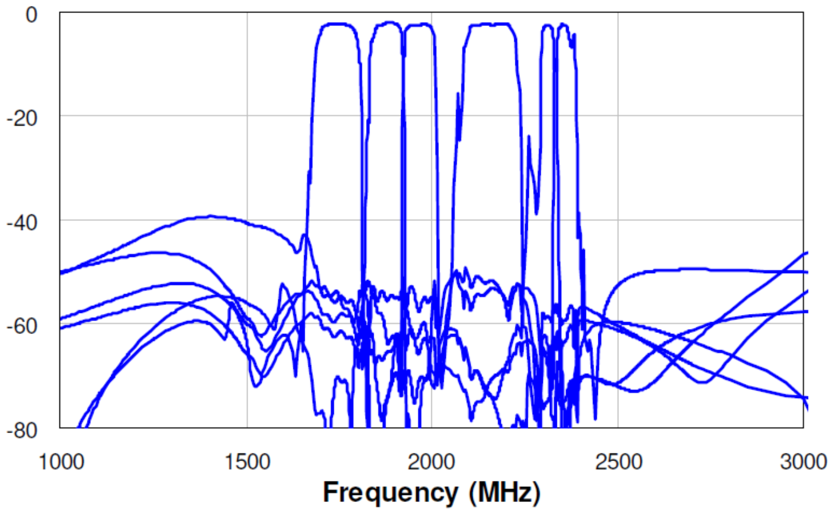


Impact of Switched Multiplexers

Example: North America CA

- Switched Multiplexing
  - Enables large number of CA combinations
  - Optimizes performance for each combination at the expense of increased complexity

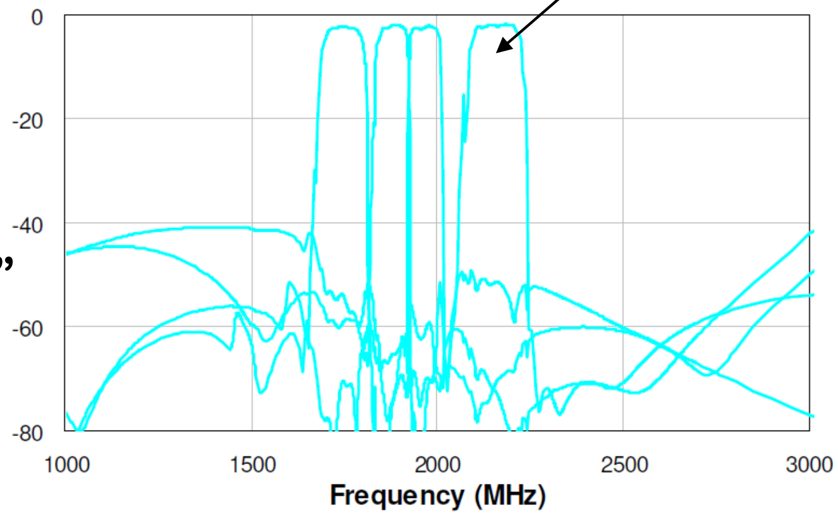
Band 25/66/30



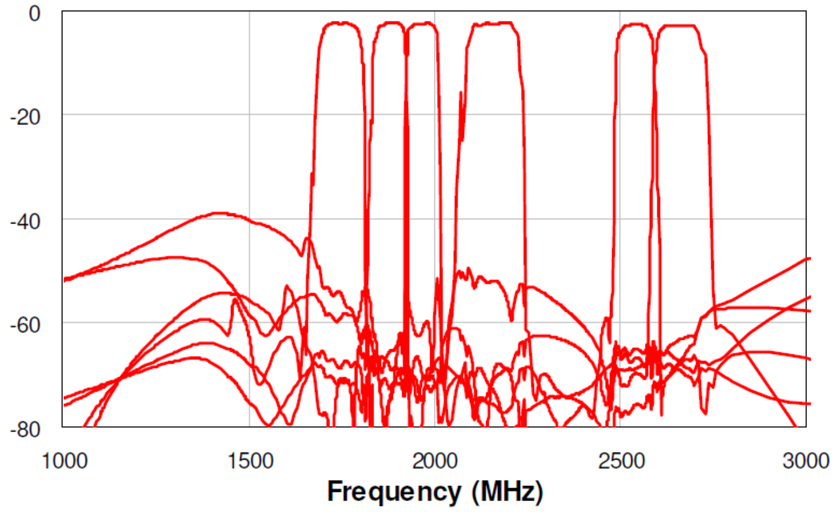
Band 25/66

"Pass Band"

"Rejection"

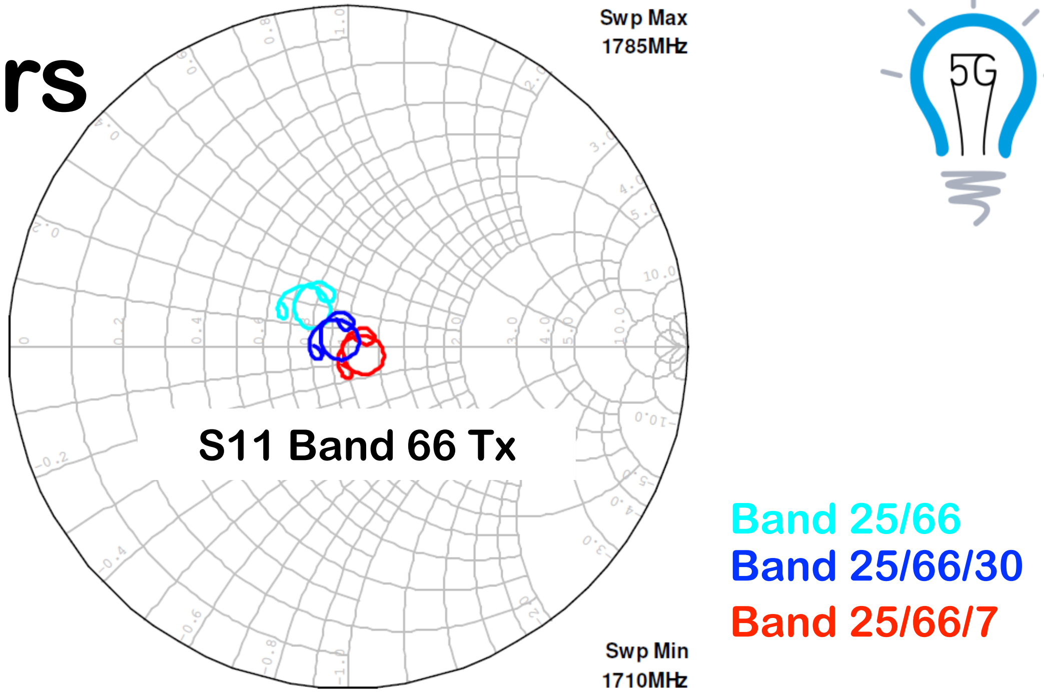


Band 25/66/7



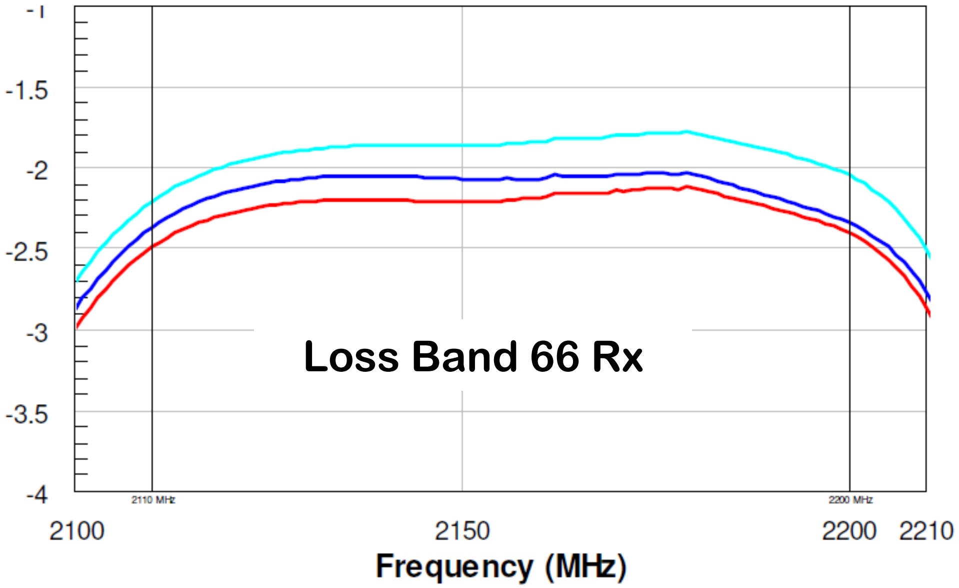
Impact of Switched Multiplexers

Impact of switched loading



Switched combinations increase matching complexity:

- Optimized loading reduces losses, thereby improving battery life and sensitivity (Rx Data rate)
- Impedance variation affects transmit performance
- Negative impact on resistive losses and mismatch losses

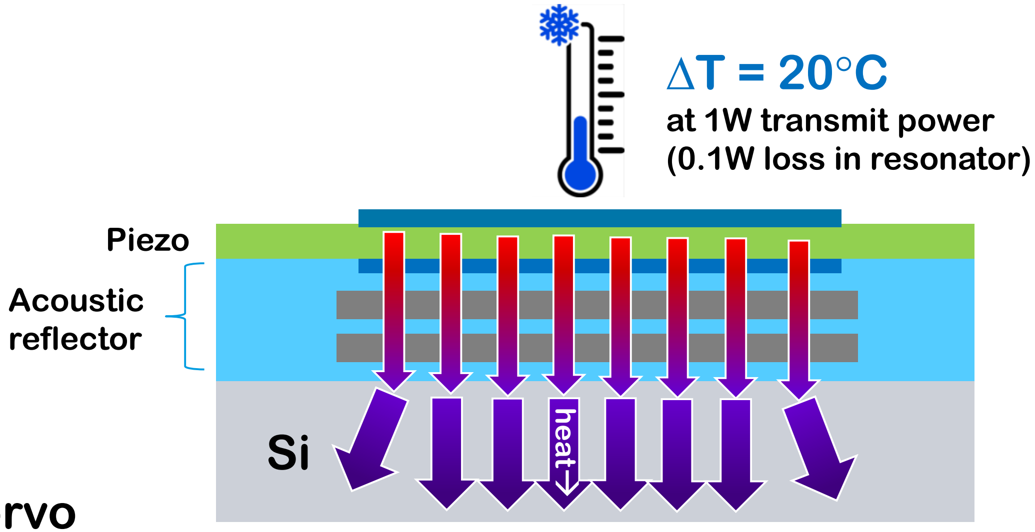


5G Filter Power-Handling

BAW-SMR and FBAR challenges, especially for higher frequencies

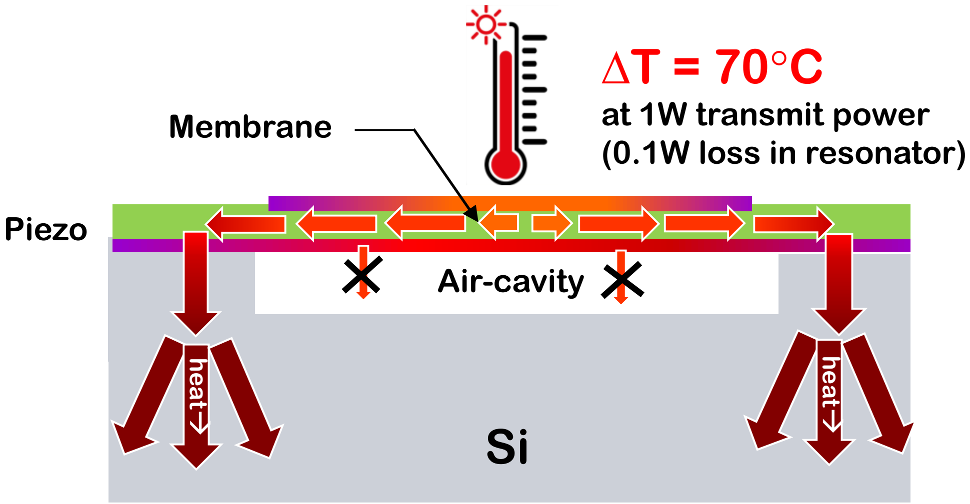
Vertical heat flux in BAW Solidly Mounted Resonator

At high frequency, thinner reflector layers
= improved heat extraction



Lateral heat flux in Film Bulk Acoustic Resonator

At high frequency, thinner membranes
= degraded heat extraction



Result: Thermal management at high transmit power is critical to prevent resonators from overheating; alternative is bigger resonators → increased IL & size

5G RF will be Challenging

Choices in RF suppliers is critical to a successful deployment

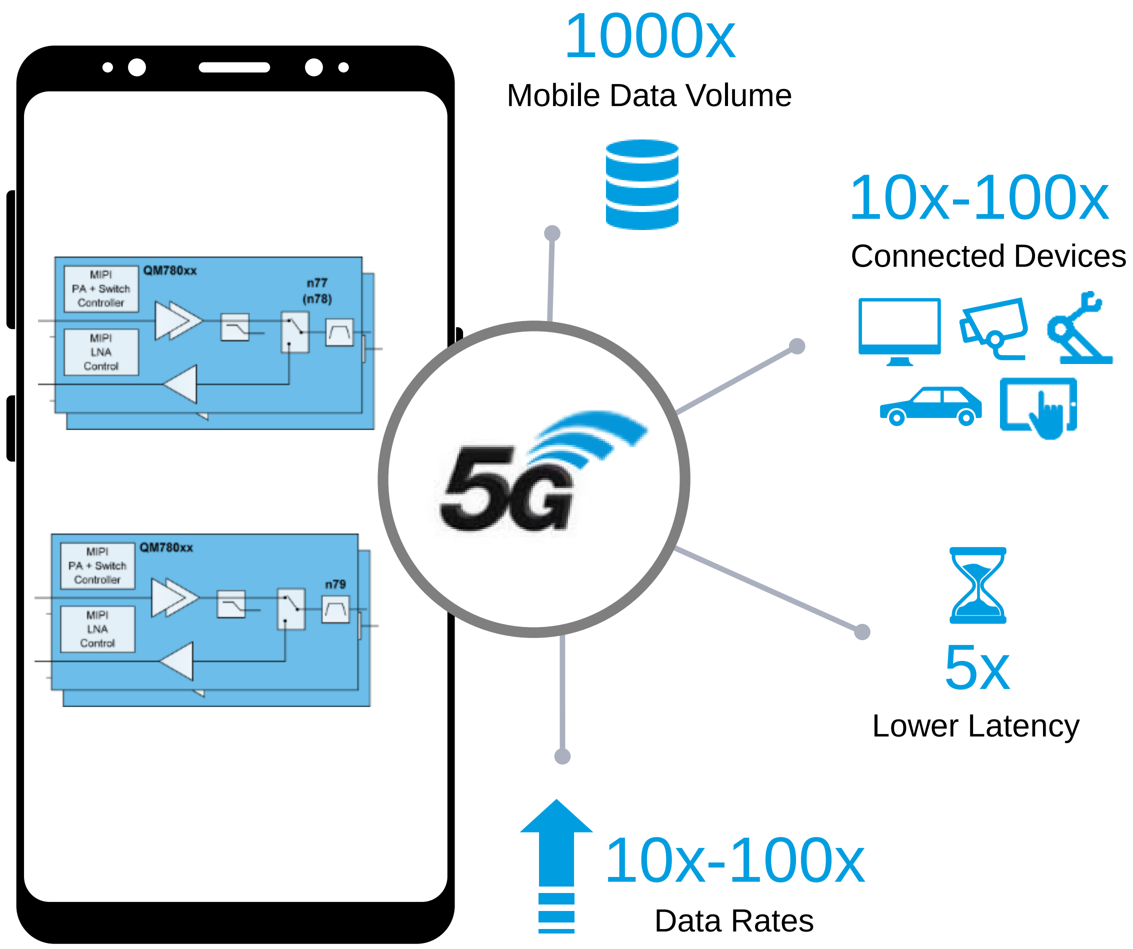
- PA: Fighting against decreased Efficiency → Less Battery Life
  - Consider 2 Waveforms & Modulations
  - Design for both EVM and ACLR
  - At many different Tx power levels
  - In both APT and ET to satisfy varying, complex EN-DC combinations
- Filter: Fighting against further decreased Battery Life and Rx coverage & data rates
  - Satisfy complex CA cases by utilizing advanced multiplexers
  - Balancing both Tx IL (Battery life) and Rx IL (data rate, Rx coverage)
  - Survive high Tx power with robust filter designs
- Overall: Fighting Time to Market, Cost and Implementation Risk

Look for 5G RF Suppliers who:

- Have a strong history of success in LTE, the backbone of 5G
- Have deep system level knowledge
- Are focused on building a solution, not just selling a product
- Can deliver a portfolio, not just a few components component

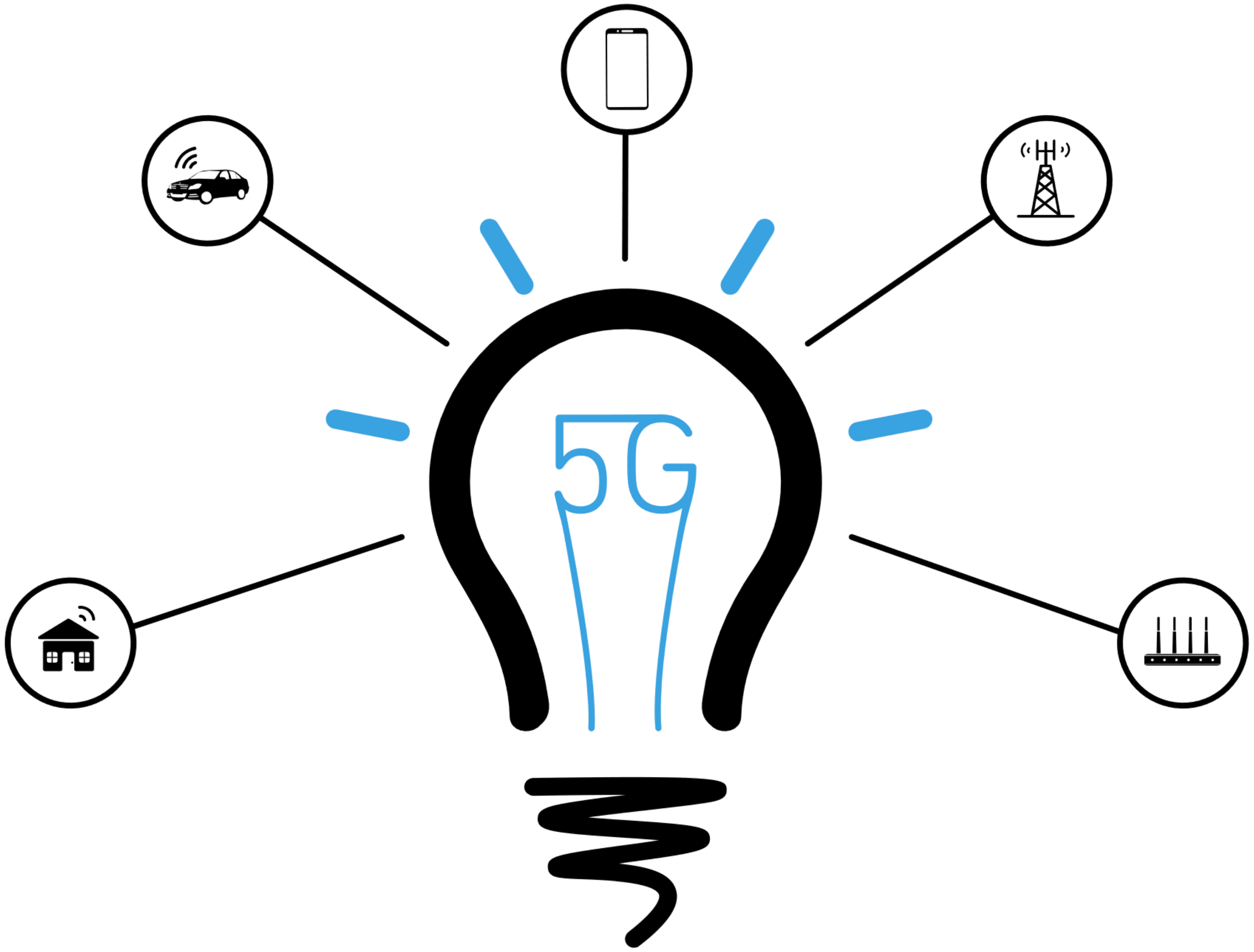
Simplifying the Complex 5G NSA CA/UL Case

Qorvo Mobile 5G portfolio



Qorvo's 5G NR FR1 portfolio addresses 4G and 5G eMBB handset challenges of ever-increasing CA modes, complex 4x4 MIMO antenna architectures, difficult coexistence requirements and space constraints by innovative integration of best-in-class filters, power amplifiers, high performance switches and LNAs, antenna tuners, and antenna-plexers.

- **Providing a complete, global CA Platform**
- **Enabling challenging UL/DL MIMO**
- **Integration for smallest RF solution size**
- **Optimized for flexibility and scalability**
- **Speeding an OEM's time-to-market (TTM)**



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