Science & Engineering Council

5G: Technology Innovation under the Hood

By Mike Eddy

November 13, 2019

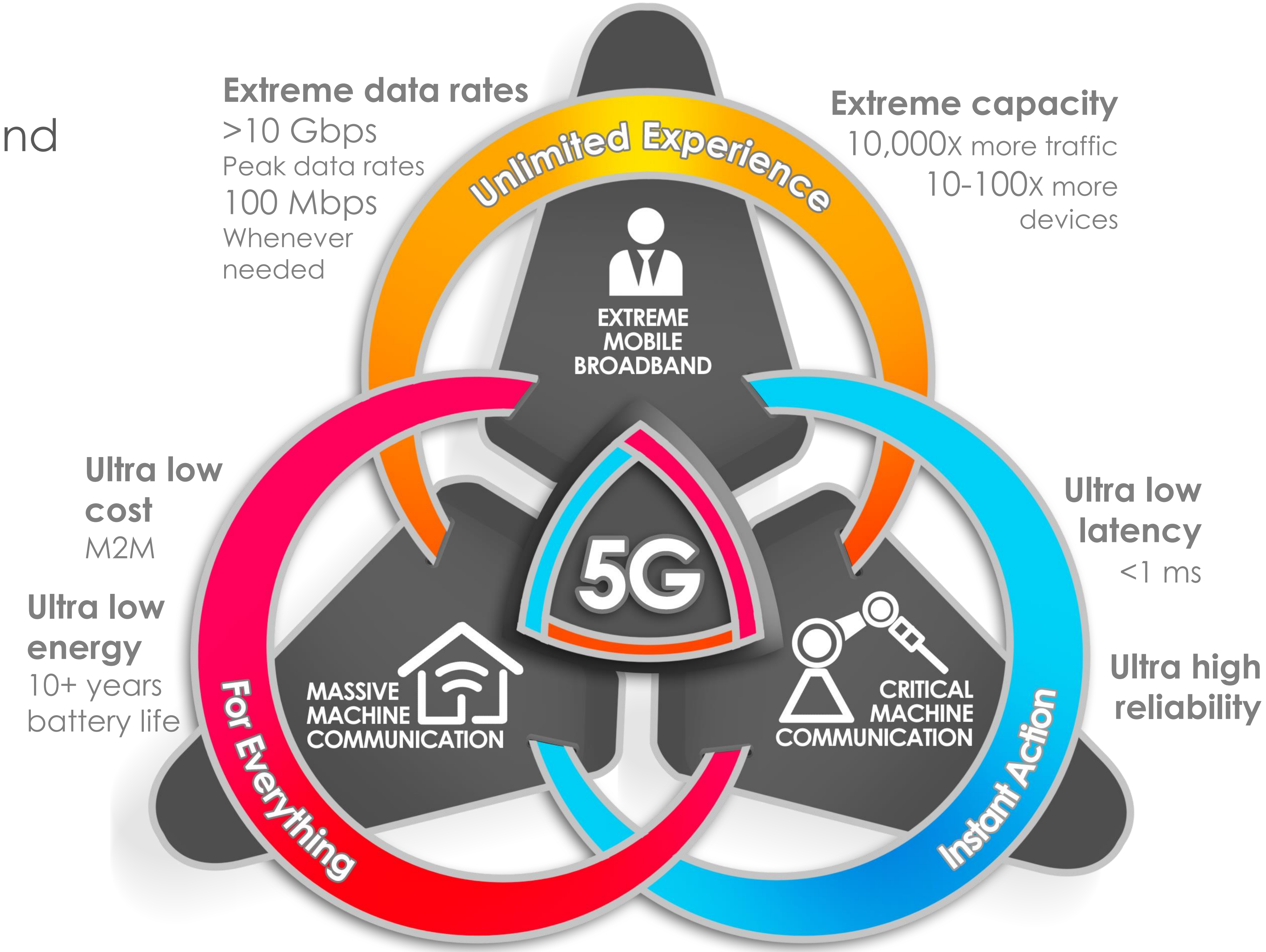
OUTLINE

- What is 5G?
- Smartphone basics
  - RF Front-end
- Market
- Key technologies
  - MIMO
  - Massive MIMO: Beam-forming
  - Increased Bandwidth
  - Complex modulation
- Concerns/Issues
  - China – US trade war
  - Interference – weather, co-existence
- Summary

What is 5G?

3 Different Use Cases:

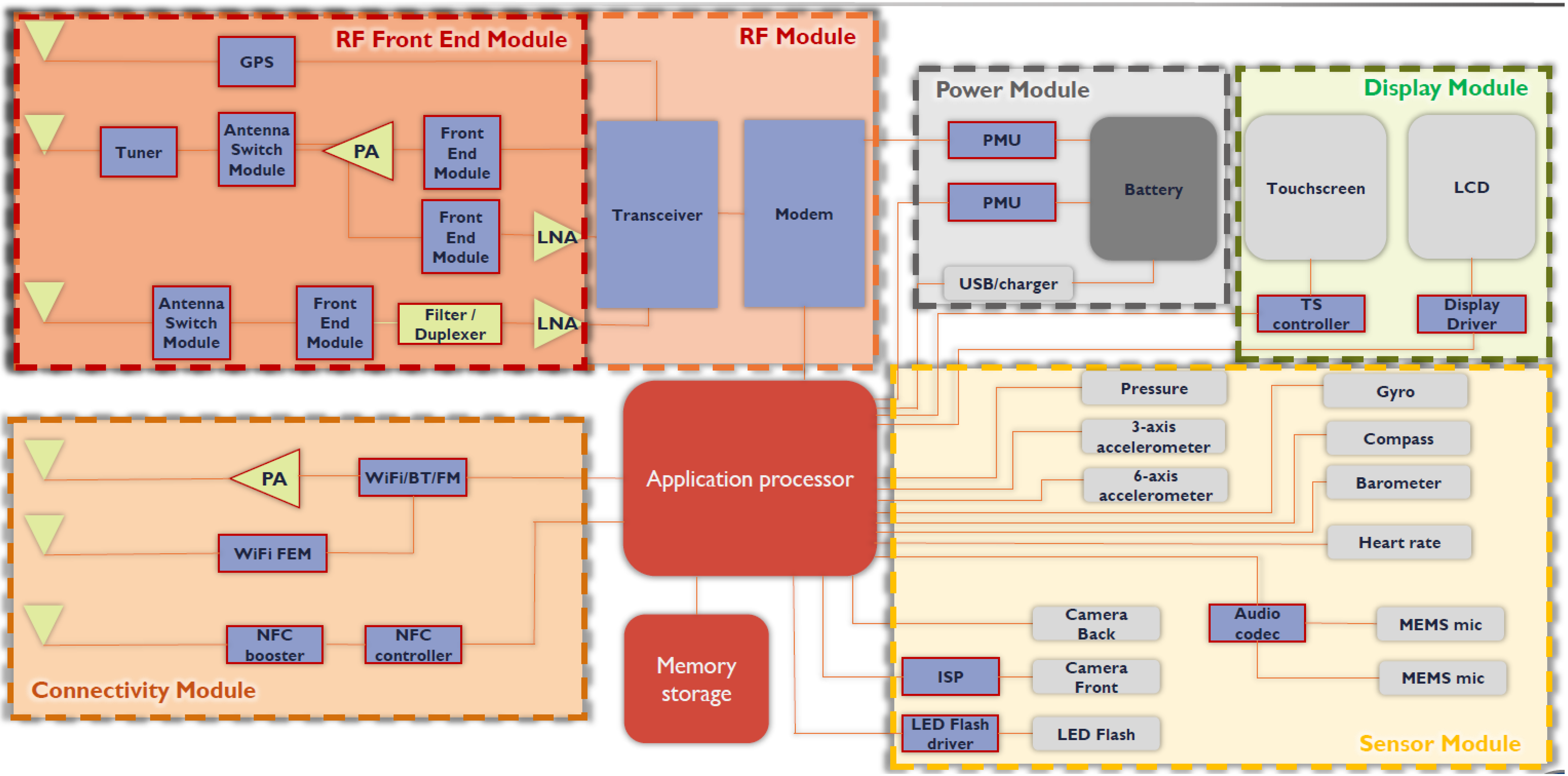
1. Extreme Mobile Broadband
   a. HD Video
2. Massive MTM Comm.
   a. IoT
3. Critical Machine Comm.
   a. High reliability



Source: Nokia

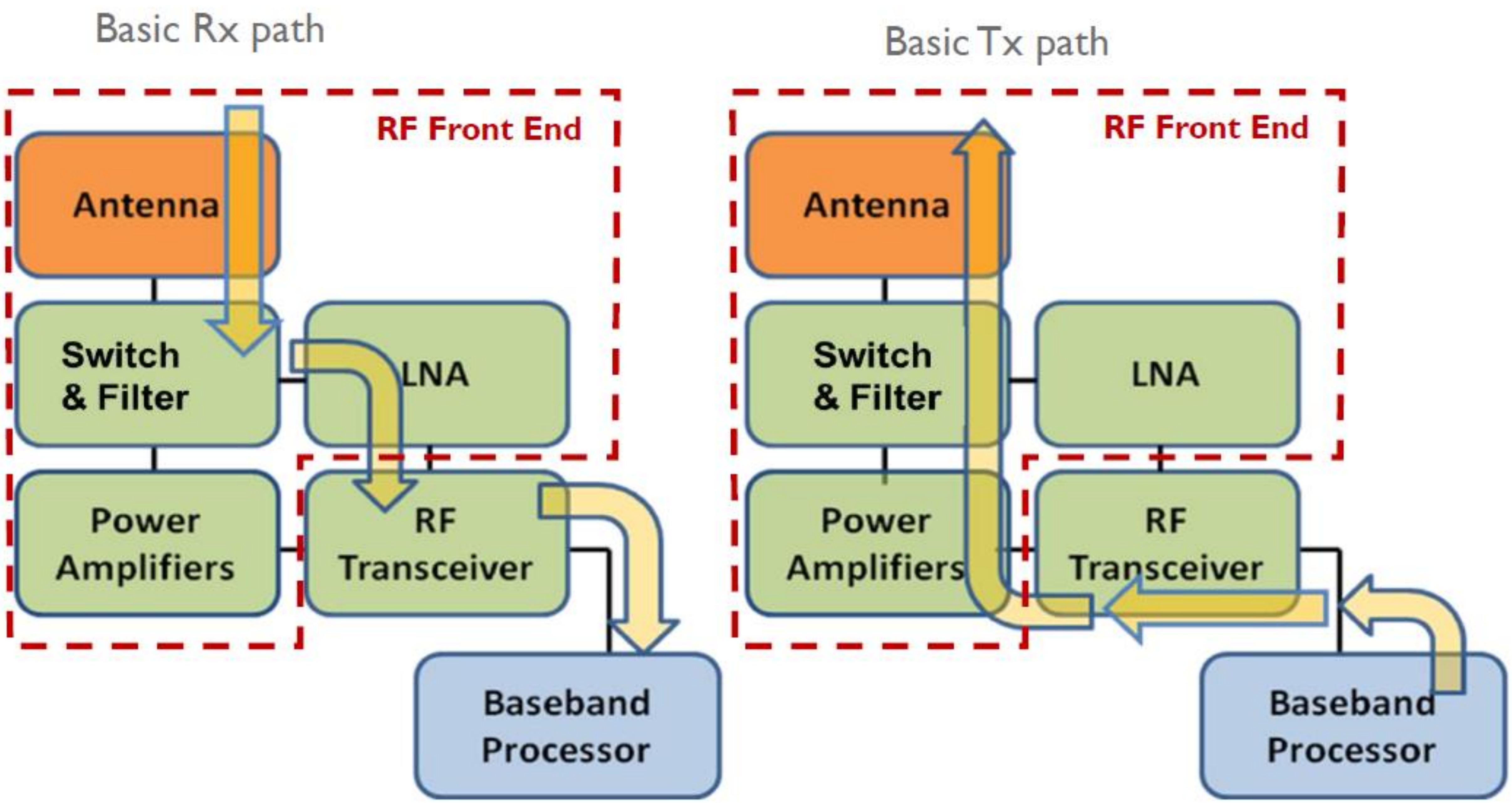
Smartphone Basics

Basic Modules in a Smartphone



Source: Yole Developpment

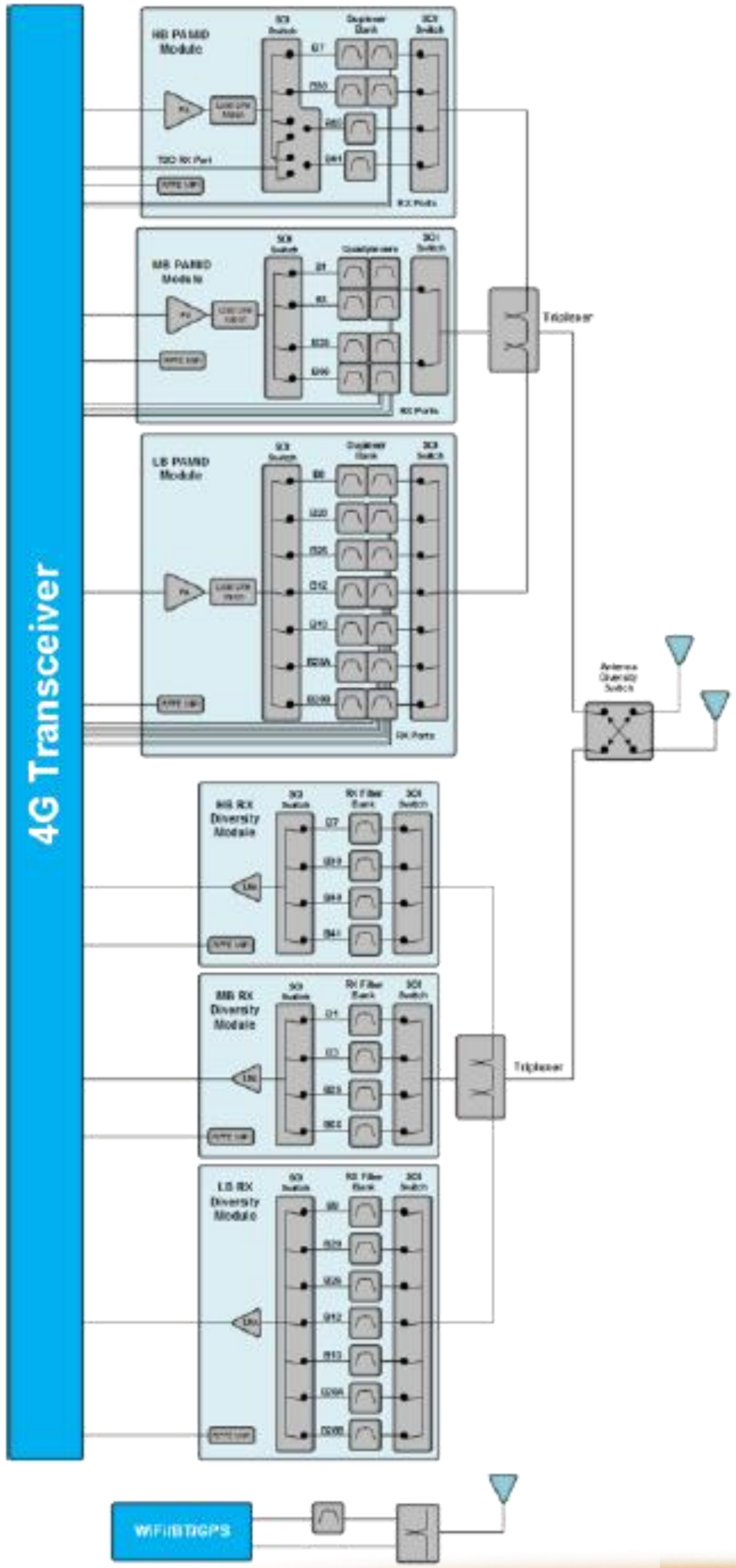
MAIN RF COMPONENTS IN A SMARTPHONE



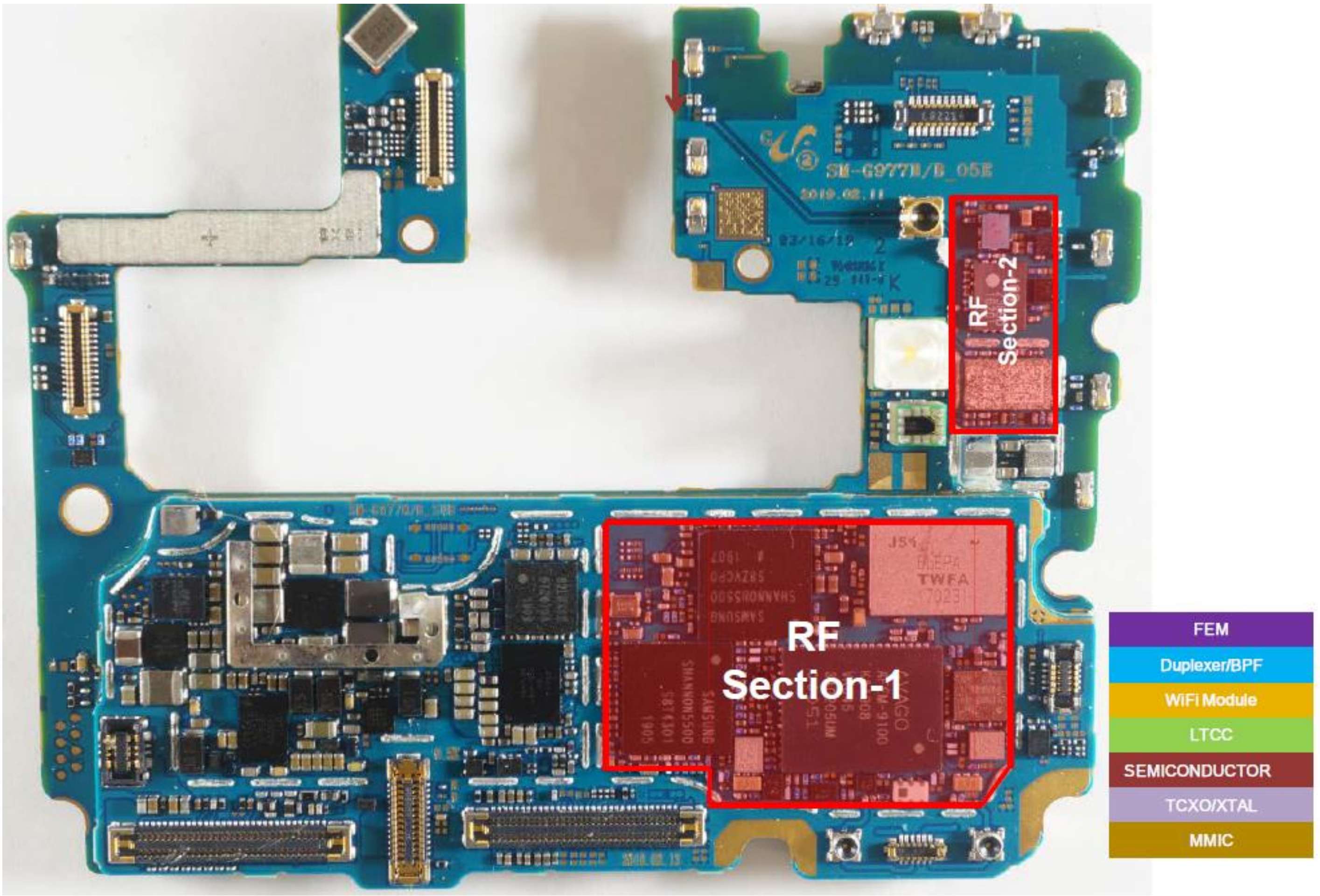
Source: Yole Developpment

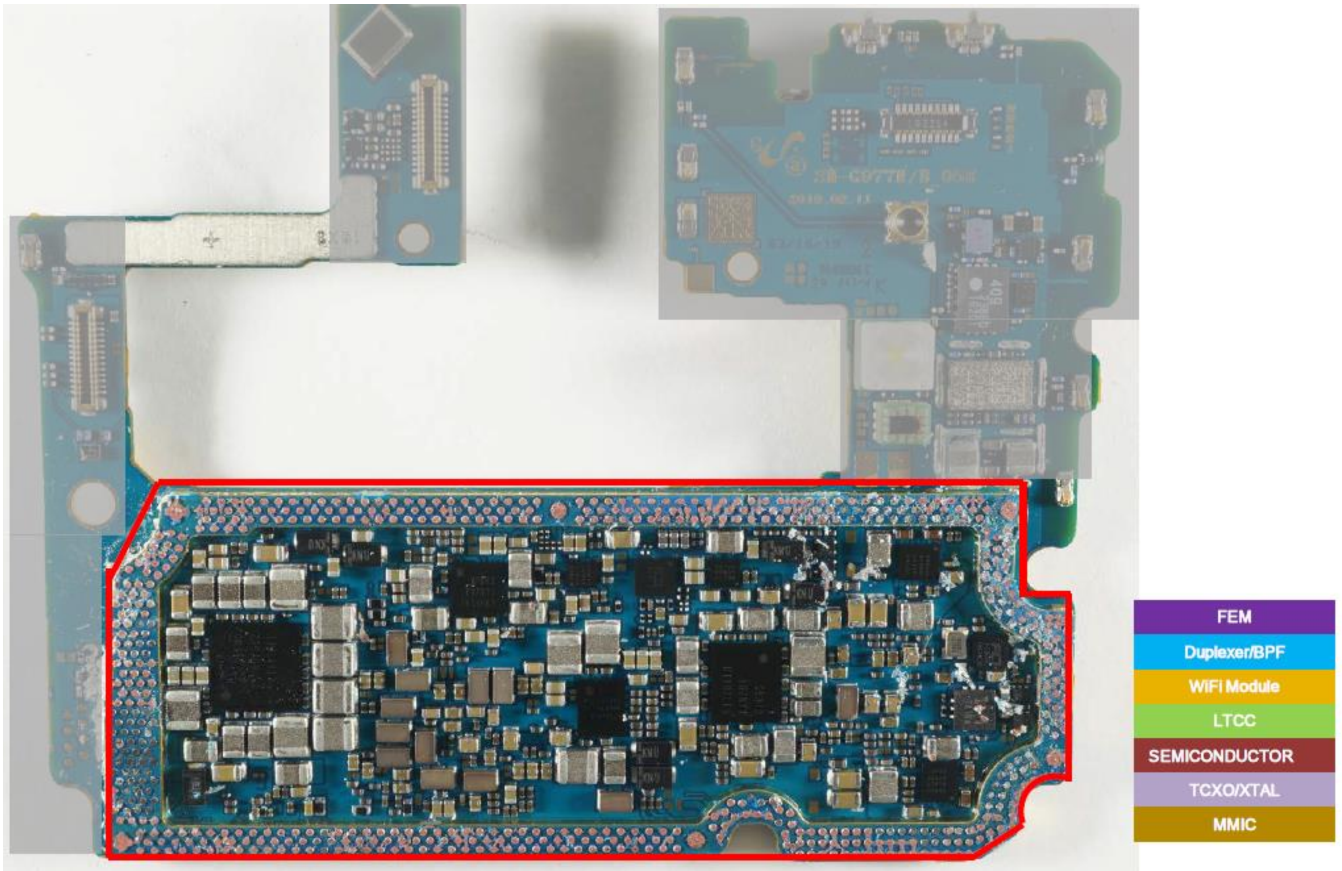
4G : RF FRONT-END ARCHITECTURE

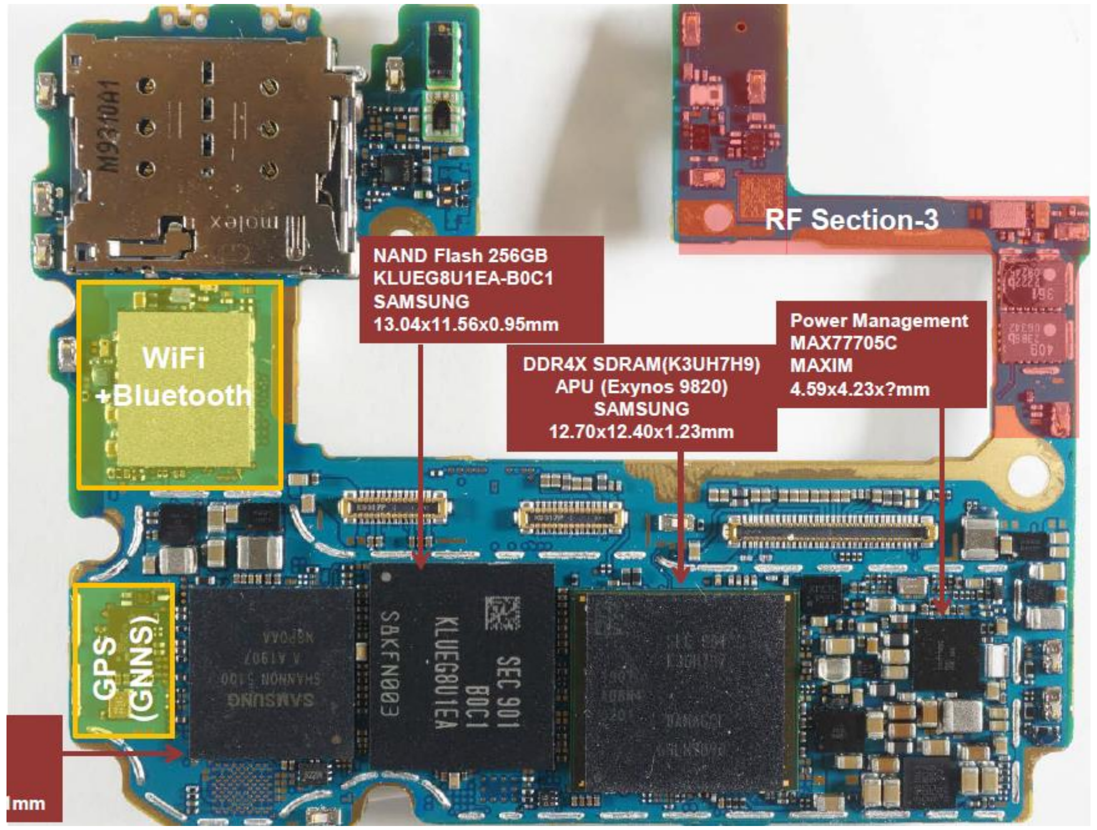
- Current requirements
  - Multiple Antennas
  - Multiple Duplexers/Filters
  - Multi-Mode, Multi-Band Power Amplifiers
  - Switches
  - Tuning Elements
  - Diversity (increased throughput)
  - Carrier Aggregation
  - WiFi Module
  - GPS Module



5G PhoneBoard Teardown





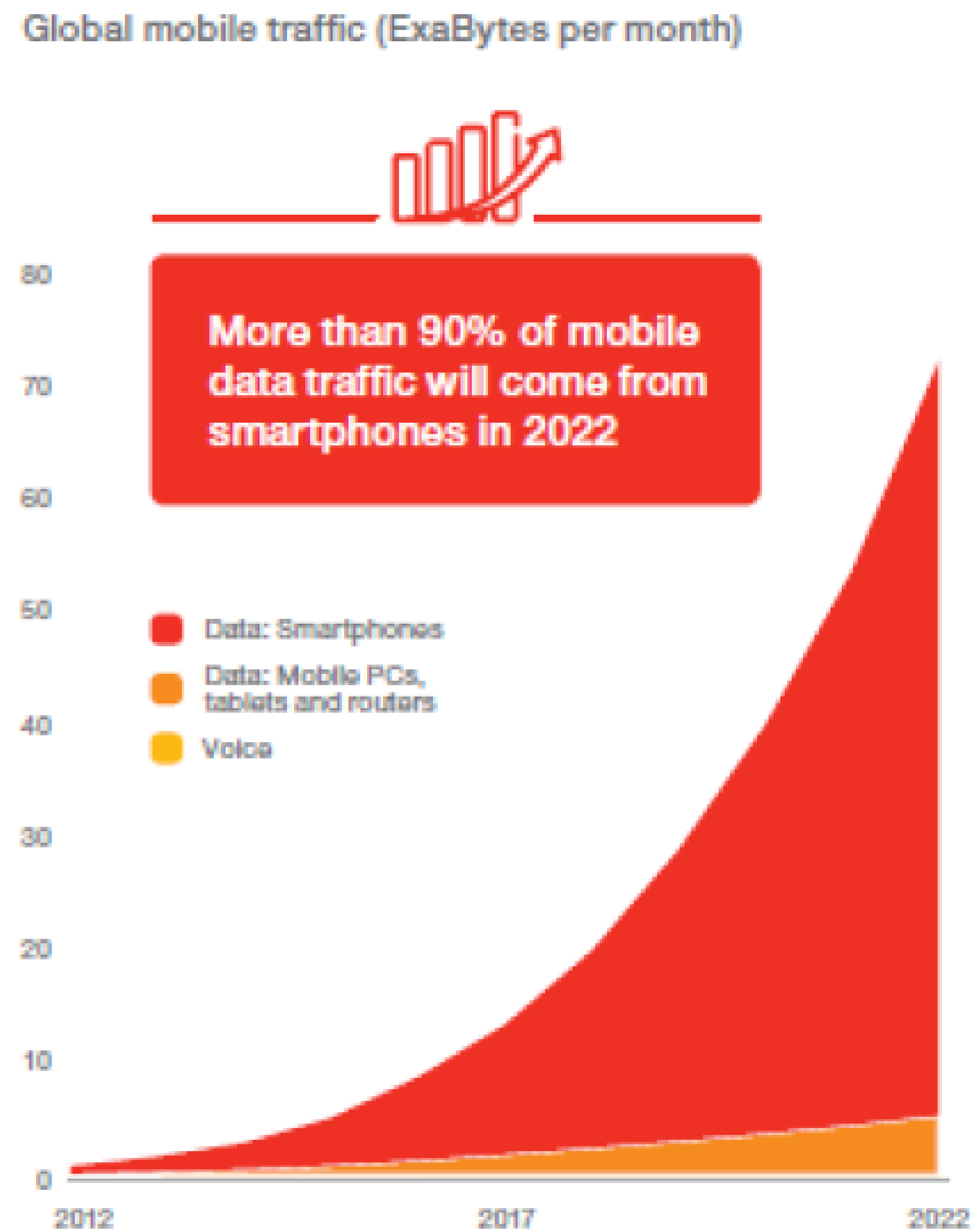


- Samsung Galaxy S10 5G
  - Launched in South Korea on April 2019
  - 1,158 phoneboard components
  - No mmWave
  - Only 1 sub-6GHz band

5G & Market Growth

MARKET DRIVER : DATA

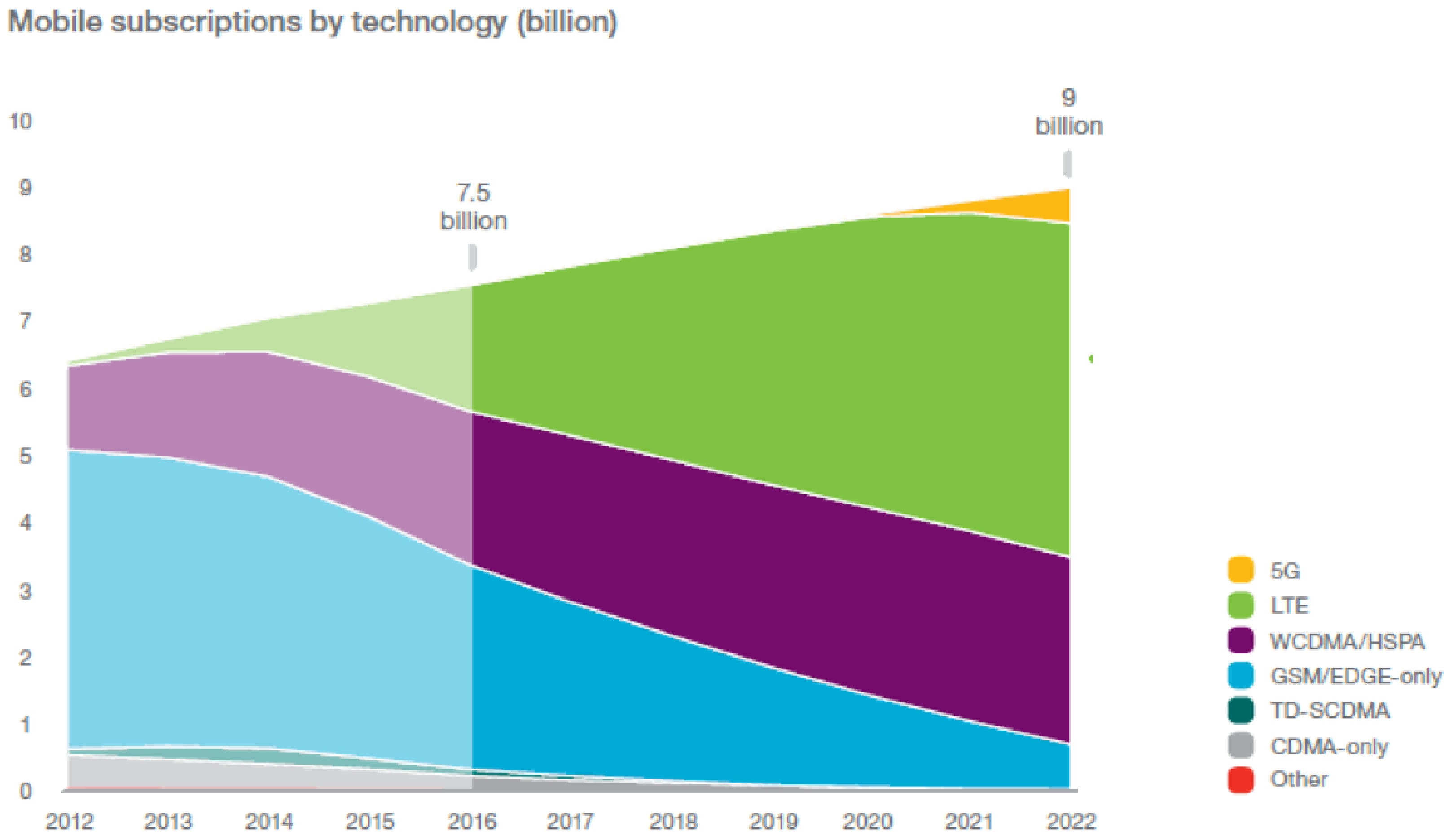
- Smartphones are estimated to handle more than 90% of data traffic by 2022
- Video will account for about 75% of this data traffic



Source: Cisco VNI

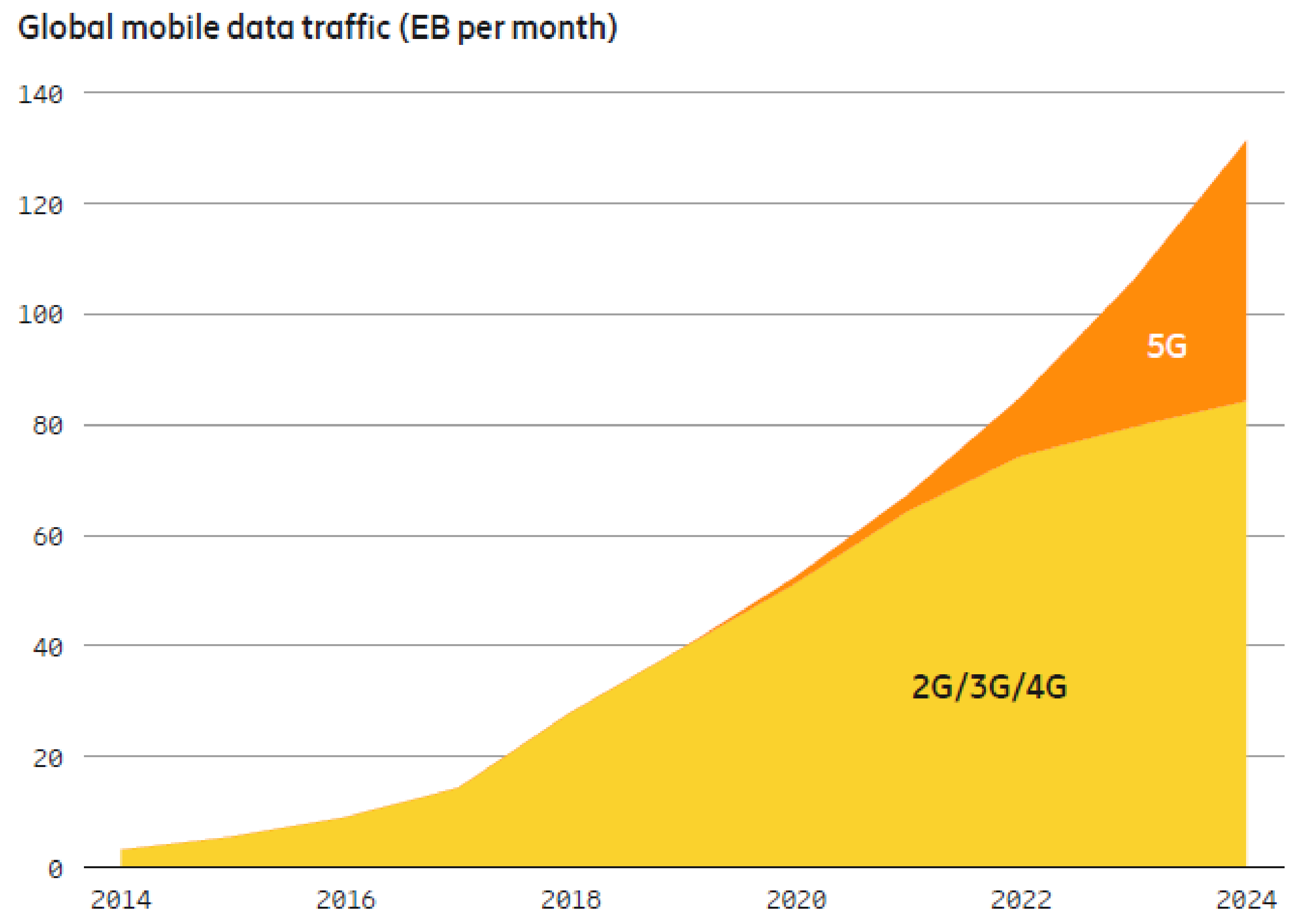
5G: ANTICIPATED GROWTH

Subscribers



Source: Cisco, Yole

Data Traffic



Source: Yole

Network Infrastructure

Ericsson : 5G population coverage using sub-6GHz and mmWave is forecast to reach 45 percent in 2024 Source: Ericsson Mobility Report 2019

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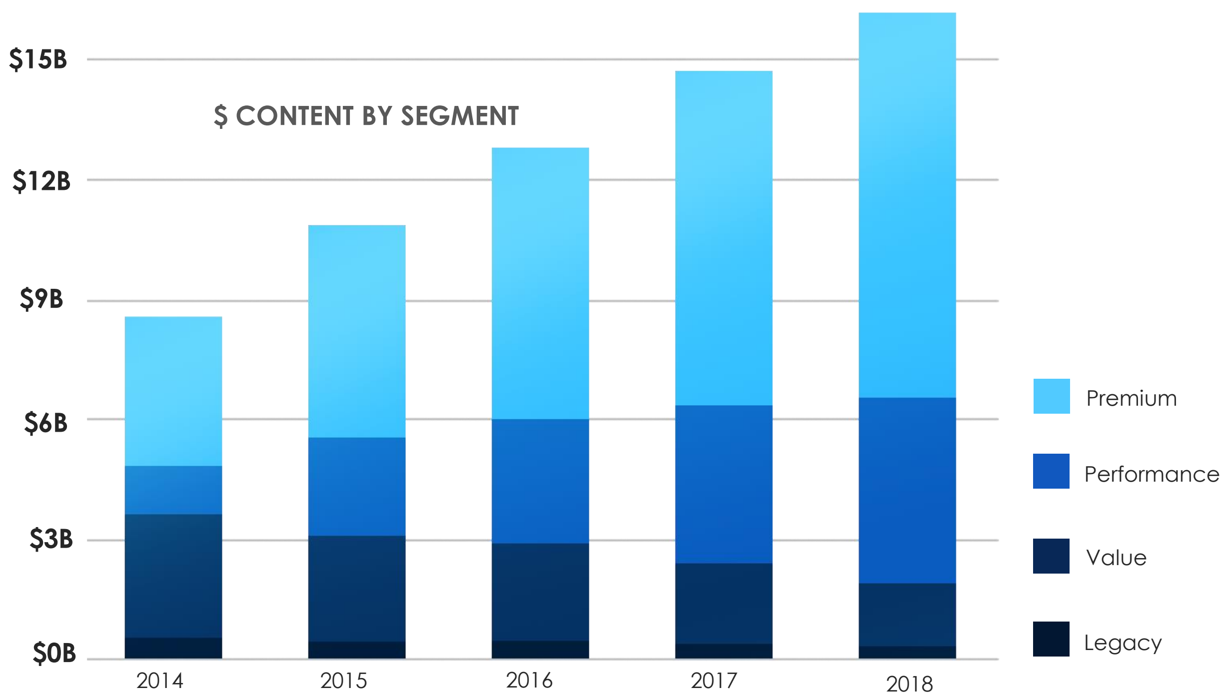
RF FRONT-END BILL OF MATERIALS

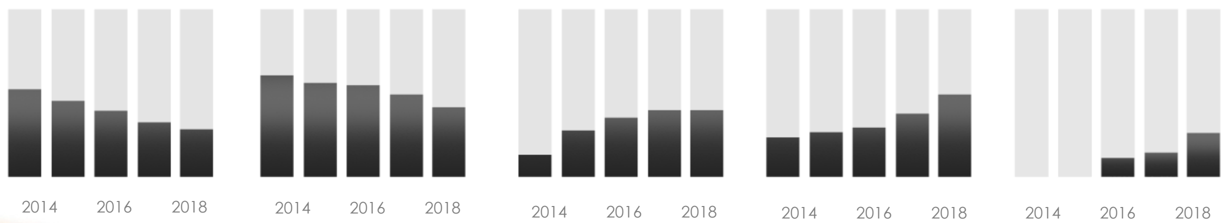
Increasing Value of RF Content | Higher RF Content Driving TAM Growth

Transition to Performance, Premium Driving up RF TAM

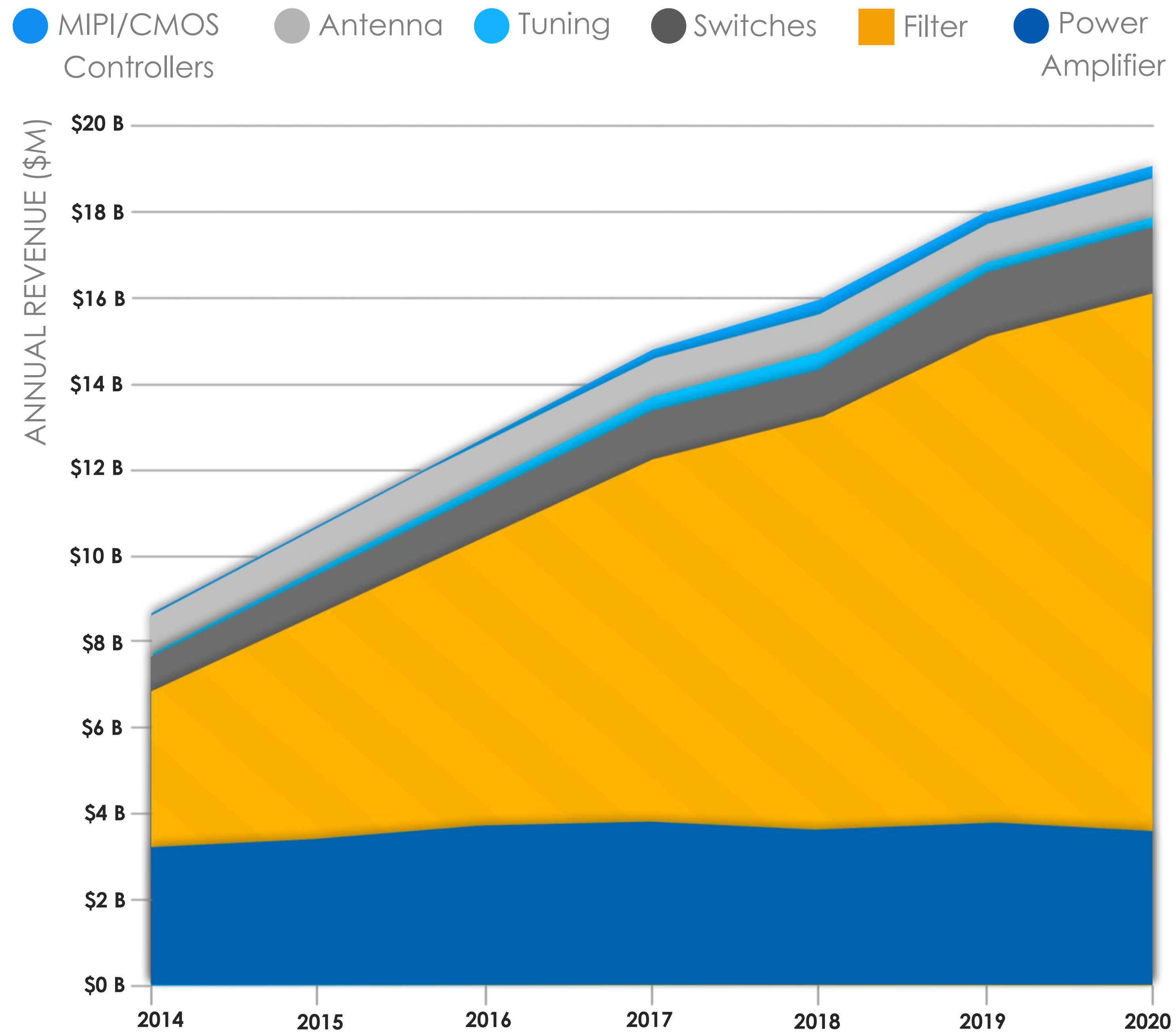


Average RF Content / Handset

Unit Shipments Trend



Source: Management Estimates, Barclays

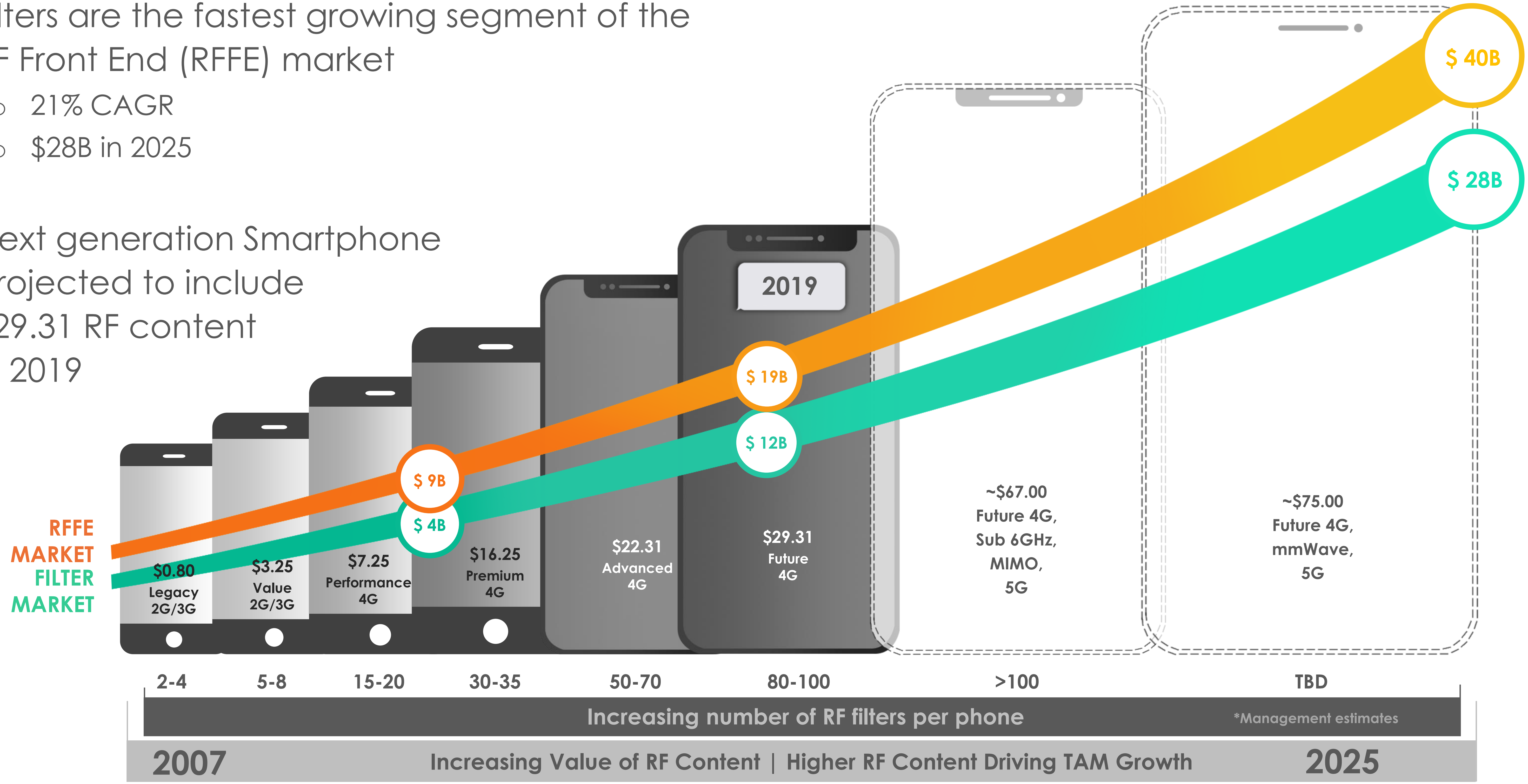


Source: Mobile Experts LLC

Filter Market growing at 23% CAGR

RF Front End Enables Mobile Phone Growth

- Filters are the fastest growing segment of the RF Front End (RFFE) market
  - 21% CAGR
  - $28B in 2025
- Next generation Smartphone projected to include $29.31 RF content in 2019

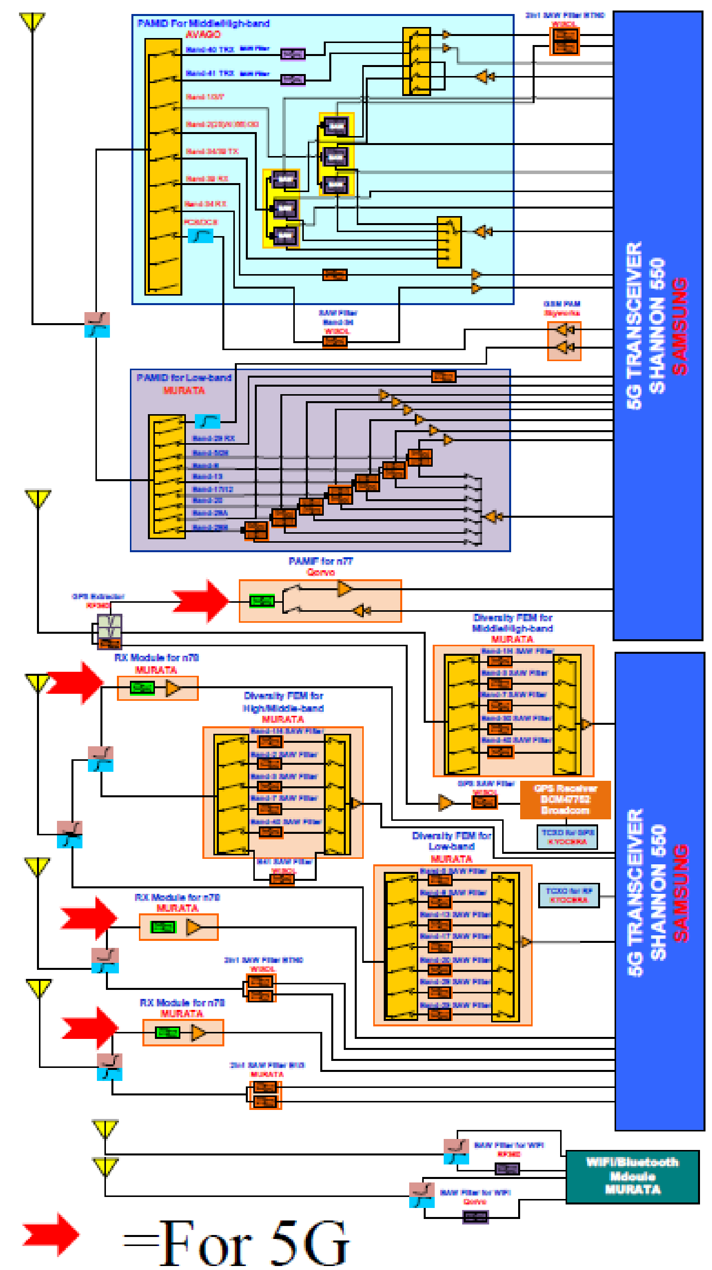


Sources: Yole Developpement, Navian, Barclays, Management Estimates

5G: Increasing Bandwidth – Implications for Smartphones

Screen : Size and Resolution

RFFE: Complexity



Source: Navian

Processor: Speed

KEY TECHNOLOGIES

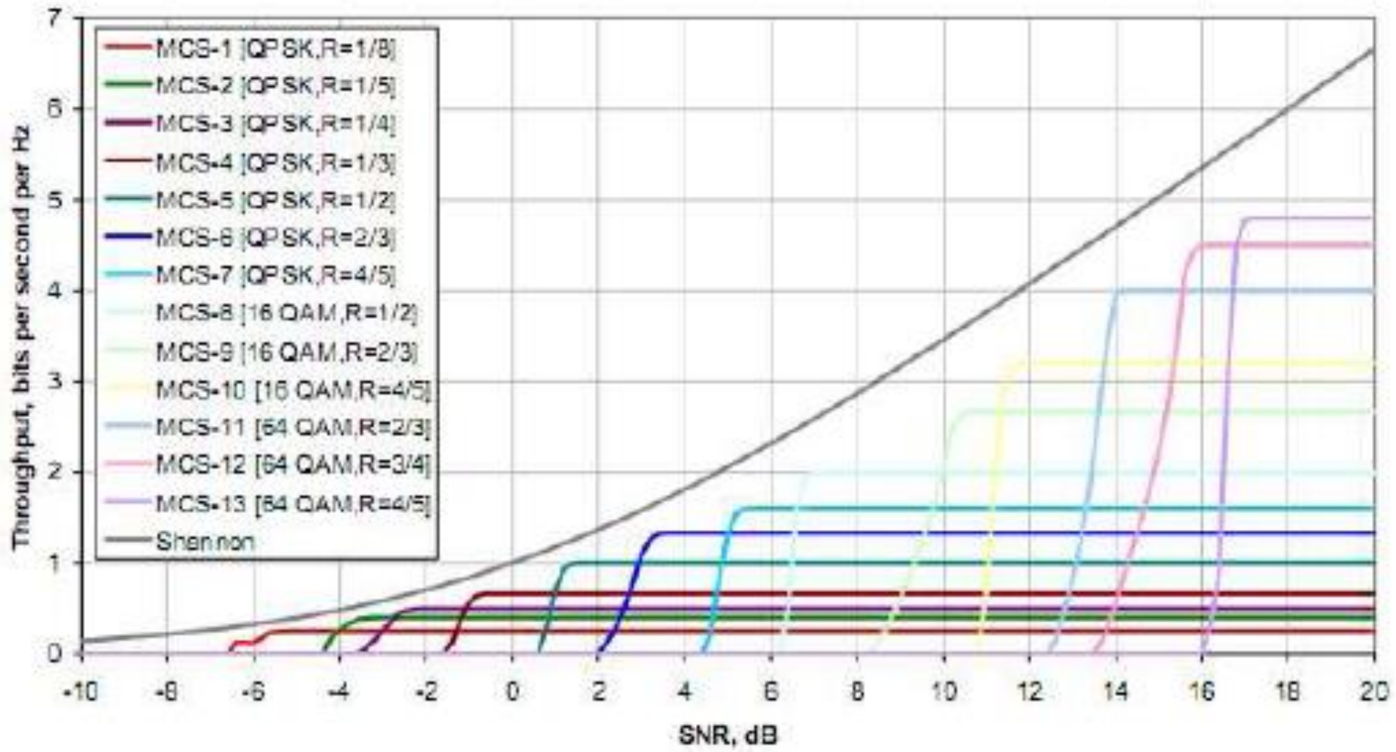
5G: Data-Rate

Shannon Theory

Maximum Wireless Data-Rate

Shannon Theory : $C = M^{*} H * \log_2 (1+SINR)$

	Description
C	Channel Capacity in bits/second
M	Number of Channels
H	Bandwidth
SINR	Signal to (Interference + Noise) Ratio



Key parameters to Increase data rate :

1) Increase bandwidth (H)
2) Increase number of channels (M)
3) Improve SINR
   a) By increasing transmit power at the user
   b) By decreasing Noise

This is achieved in 5G by:

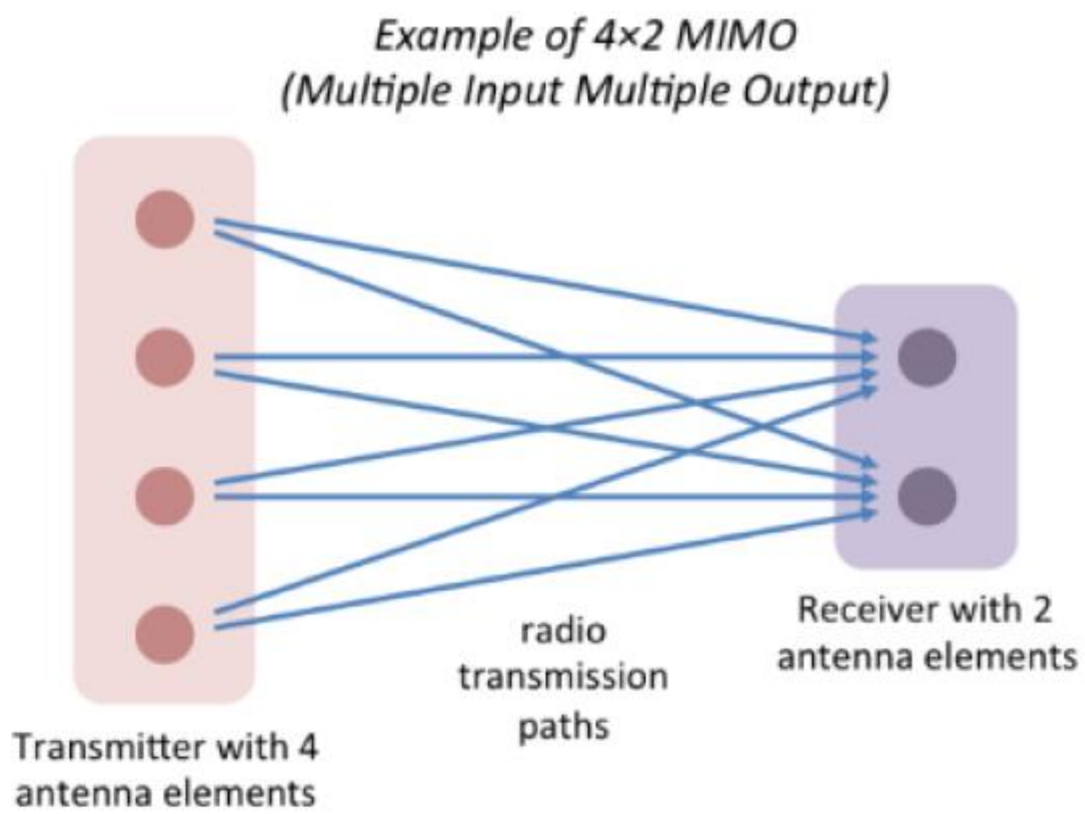
1) More instantaneous bandwidth (n77, n79..) & aggregation of spectrum
2) More antennas (MIMO)
3) Densification of the network
4) Higher order modulation schemes

5G – Key Technologies

- MIMO : Multiple Antennas
  - More RF paths requiring more RF components
  - Massive MIMO antennas for improved coverage & capacity using beamforming
- Increasing bandwidth
  - More CA. More bands. More filter complexity
  - Larger, single frequency bandwidth. Only available at higher frequencies
- More complex modulation schemes
  - Increasing number of bits/symbol
  - Requires improved SINR
- Densification of the Network
  - Small cells

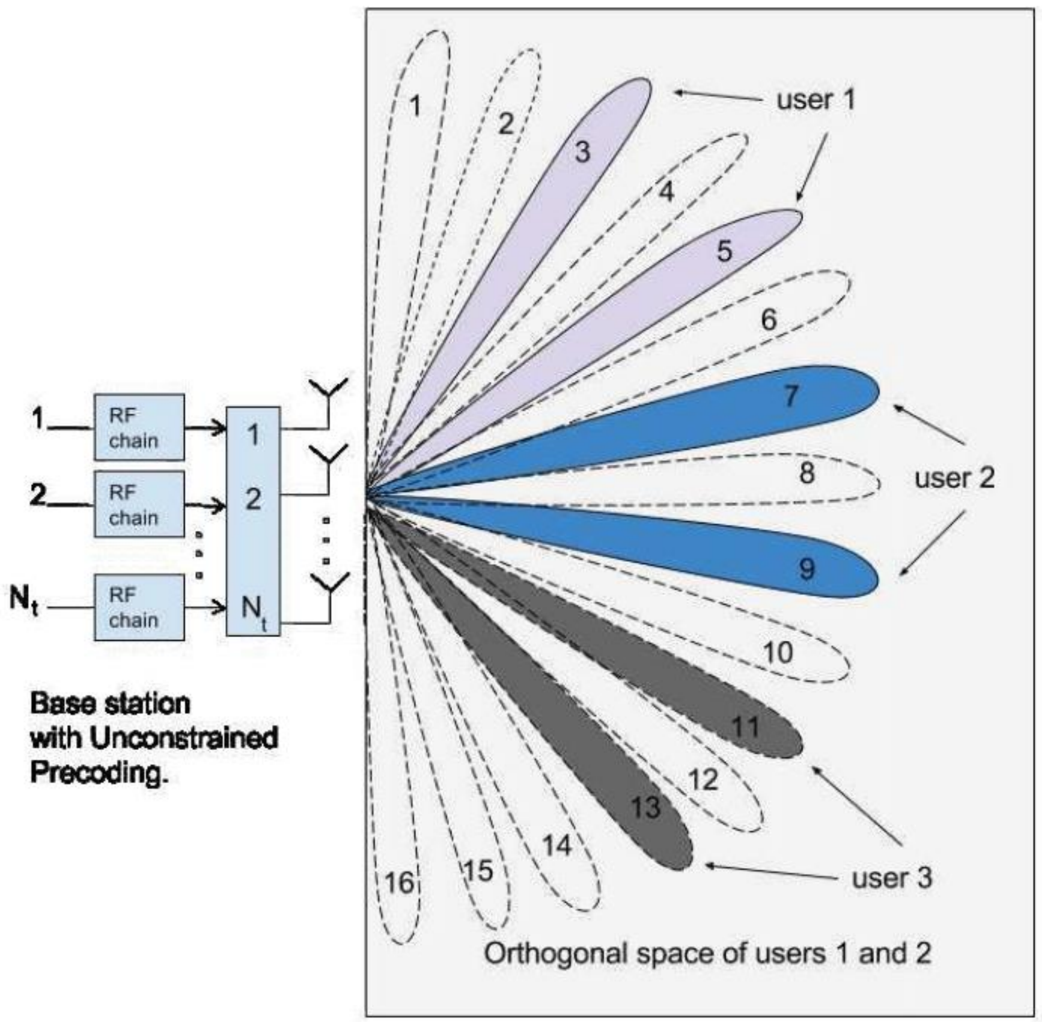
MULTIPLE INPUT MULTIPLE OUTPUT: MIMO

MIMO : 4x2



- Most effective in urban environments
- Signal split and relies on different path lengths

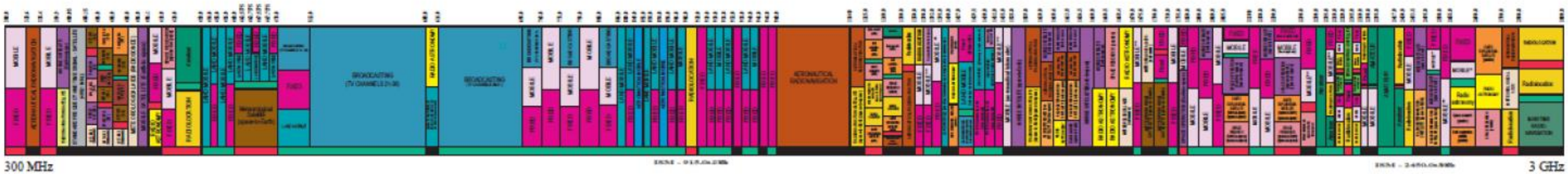
Massive MIMO : Beamforming



- Directs energy toward user
- Essential for high frequency to improve coverage
- Technically difficult, high cost

The Importance of Filters

Frequency spectrum allocation

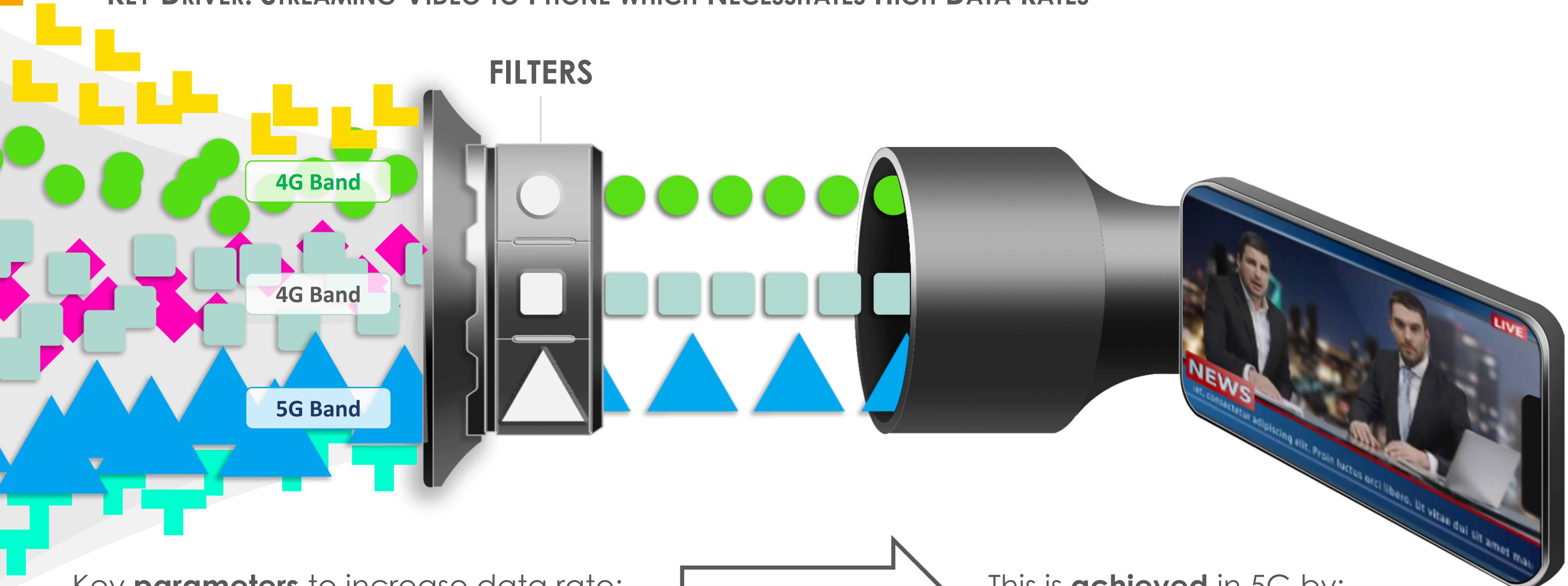


A unique filter is required for each band of operation

Source: U.S. Dept. of Commerce

5G: Extreme Mobile Broadband Drivers

Key Driver: Streaming Video to Phone which Necessitates High Data Rates



Key **parameters** to increase data rate:

1. Increase bandwidth
2. Increase number of channels
3. Improve SINR - Signal to (Interference + Noise) Ratio
    a. By increasing transmit power at the user
    b. By decreasing noise

This is **achieved** in 5G by:

1. More instantaneous bandwidth (n77, n79..) & aggregation of spectrum
2. More antennas (MIMO)
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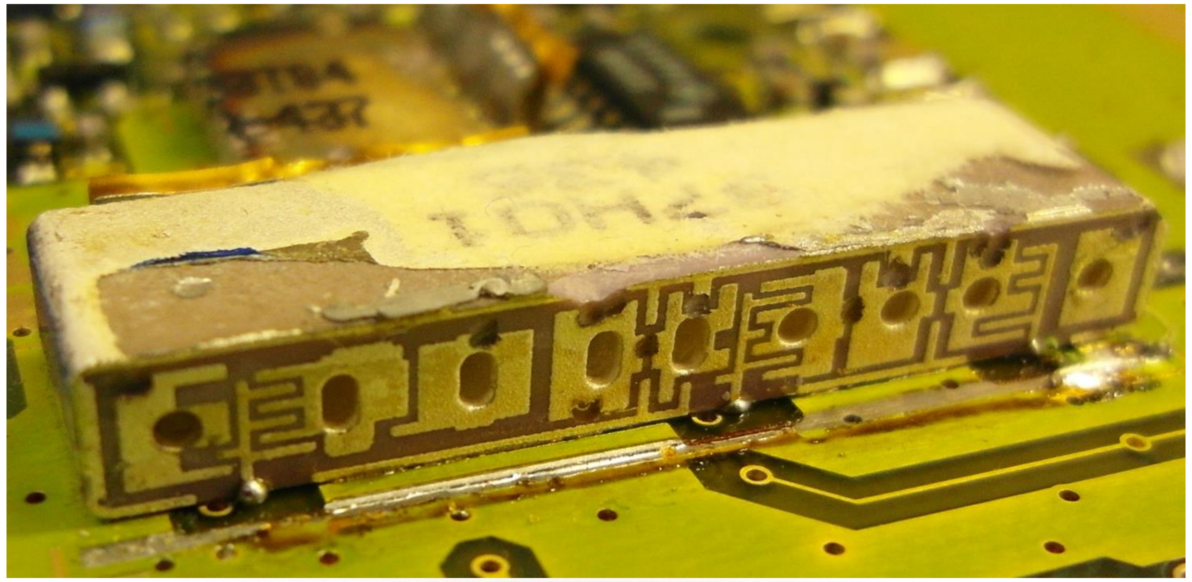
4. Higher order modulation schemes

Acoustic Wave Physics Drives Filter Size

Wave Media	Wave Velocity (km/sec)	Wave Length @ 2GHz (mm)
Electromagnetic in Air	300,000	150
Electromagnetic in High Dielectric ($\varepsilon = 100$)	30,000	15
Acoustic Wave in Solid Material	4-12	.002 - .003

- Early mobile filters used dielectric resonators
  - Too large for multiple filters/phone
- Acoustic Wave Devices allow miniaturization
  - Small size, low cost
  - Maintain performance



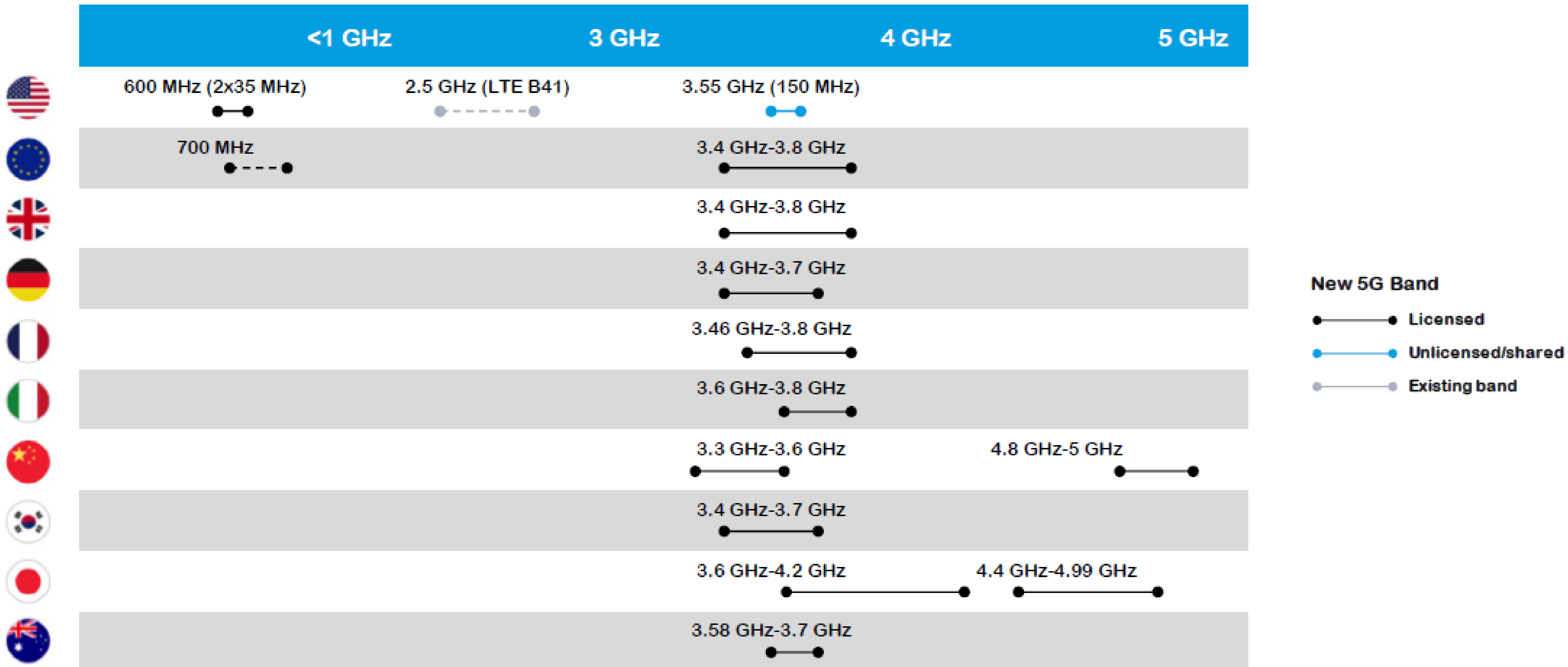
Dielectric filter from Motorola (1994)

iPhone XS : Frequency Bands & Nations Covered

1 (2100 MHz)
2 (1900 MHz)
3 (1800 MHz)
4 (AWS)
5 (850 MHz)
7 (2600 MHz)
8 (900 MHz)
12 (700 MHz)
13 (700c MHz)
14 (700 PS)
17 (700b MHz)
18 (800 MHz)
19 (800 MHz)
20 (800 DD)
25 (1900 MHz)
26 (800 MHz)
28 (700 APT MHz)
29 (700 de MHz)
30 (2300 MHz)
32 (1500 L-band)
34 (TD 2000)
38 (TD 2600)
39 (TD 1900)
40 (TD 2300)
41 (TD 2500)
46 (TD Unlicensed)
66 (AWS-3)

Andorra	Andorra Telec
Armenia	Beeline Ucom
Australia	Optus Telstra Virgin Vodafone
Austria	3 A1 T-Mobile tele.ring
Bahrain	Batelco Viva Zain
Belgium	BASE Mobistar Proximus Telenet
Bulgaria	M-Tel Telenor
Croatia	Hrvatski Telek Vip
Cyprus	Cyta MTN PrimeTel
Czech Republic	O2 T-Mobile Vodafone
Denmark	3 TDC Telenor
Estonia	Elisa EMT Tele2
Finland	DNA Elisa Saunalahti Telia
France	Bouygues Free Mobile La Poste Mobile NRJ Mobile Orange SFR Virgin Mobile
Georgia	Geocell Beeline
Germany	1&1 O2 Telekom Vodafone
Greece	Cosmote Vodafone Wind
Greenland	Tele Greenland
Hungary	Magyar Telekom Telenor Vodafone
Iceland	Nova Siminn Vodafone
India	Airtel Reliance Jio Vodafone
Ireland	3 Meteor Vodafone
Isle of Man	Manx Telecom Sure Mobile
Italy	3 TIM Vodafone Wind
Jersey	Jersey Telecom
Kazakhstan	Kcell
Kuwait	Ooredoo Viva Zain
Latvia	Bite LMT Tele2
Liechtenstein	Salt Swisscom
Lithuania	Bite Omnitel Tele2
Luxembourg	Orange Post Telecom Tango Mobile
Malta	Vodafone
Mexico	AT&T Movistar Oui Telcel
Monaco	Monaco Telecom
Netherlands	KPN T-Mobile Tele2 Vodafone
New Zealand	2degrees Spark Vodafone
Norway	Telenor Telia
Oman	Omantel Ooredoo
Poland	Orange Play T-Mobile
Portugal	MEO NOS Vodafone
Qatar	Ooredoo Vodafone
Romania	Orange Telekom Vodafone
Russia	Beeline MegaFon MTS Tele2 Yota
Saudi Arabia	Mobily STC Zain
Singapore	M1 Singtel StarHub
Slovakia	Orange Slovak Telekom
Slovenia	A1 Slovenija Telekom Slovenia
South Africa	CellC MTN Vodacom
Spain	Orange Vodafone Yoigo
Sweden	3 Tele2 Telenor Telia
Switzerland	Salt Sunrise Swisscom UPC Wingo
Taiwan	APT Chunghwa Telecom FarEasTone Taiwan Mobile Taiwan Star
United Arab Emirates	du Etisalat
United Kingdom	3 BT EE Giffgaff O2 Sky Virgin Mobile UK Vodafone

5G: SUB 6GHZ SPECTRUM



5G's Impact on the RF Front End – Technology

5G demands larger bandwidth that is only available at higher frequency

5G Requirements	XBAR
Large bandwidth *100's of MHz vs. 10's of MHz*	✓
High frequency (3GHz - 80GHz) *Only frequencies where large bandwidths are available*	✓
Power handling *High frequency = less propagation* *Overcome with higher power to increase coverage*	✓
High quality factor, Q, of resonator structure *Determines rejection and loss of the filter* *Particularly challenging at high frequency*	✓

Based upon simulation results
Initial measured verification in process

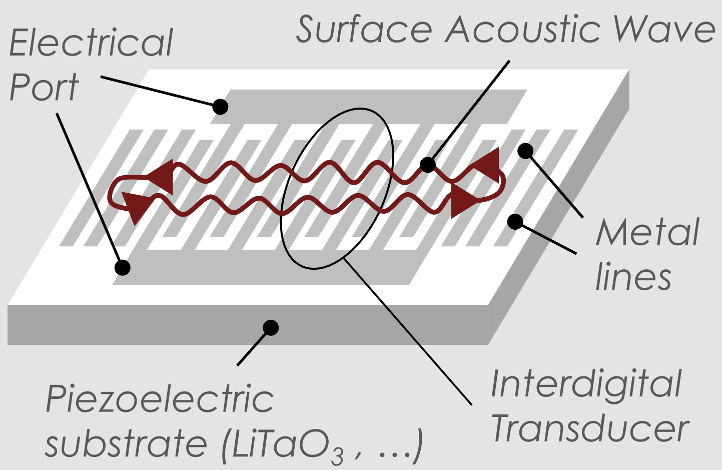
What is XBAR?

- Proprietary resonator structure based on existing process technologies developed using ISN
  - IP/ XBAR based library products for 5G

ACOUSTIC WAVE FILTER TECHNOLOGIES

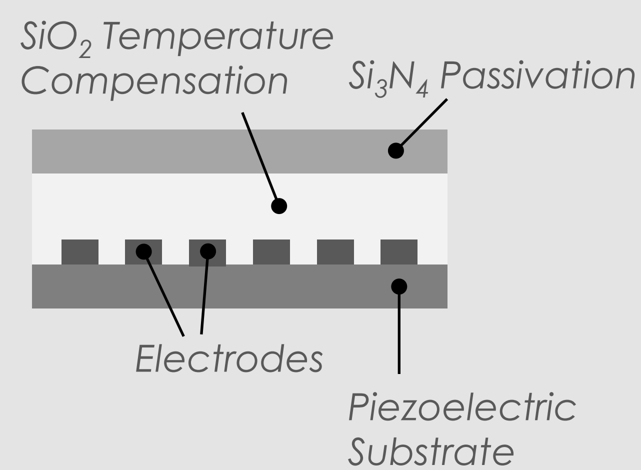
SAW
Surface Acoustic Wave

Acoustic wave propagates in a ***lateral*** direction



TC-SAW
Temperature-Compensated SAW

Acoustic wave propagates in a ***lateral*** direction

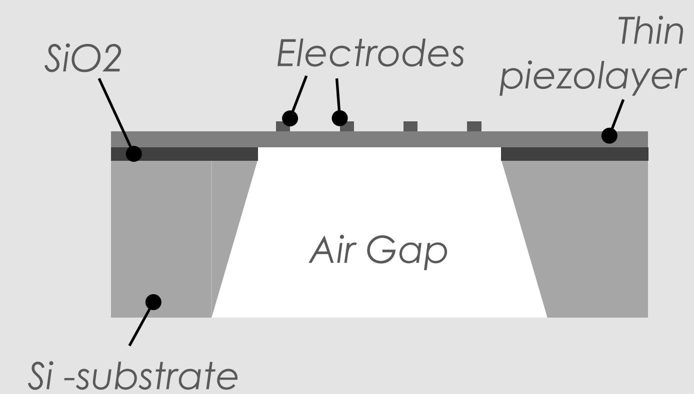


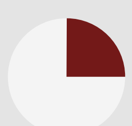
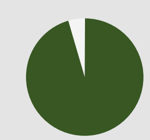
FBAR
Bulk Acoustic Wave

Acoustic wave propagates in a vertical direction

BAW – XBAR™
Bulk Acoustic Wave

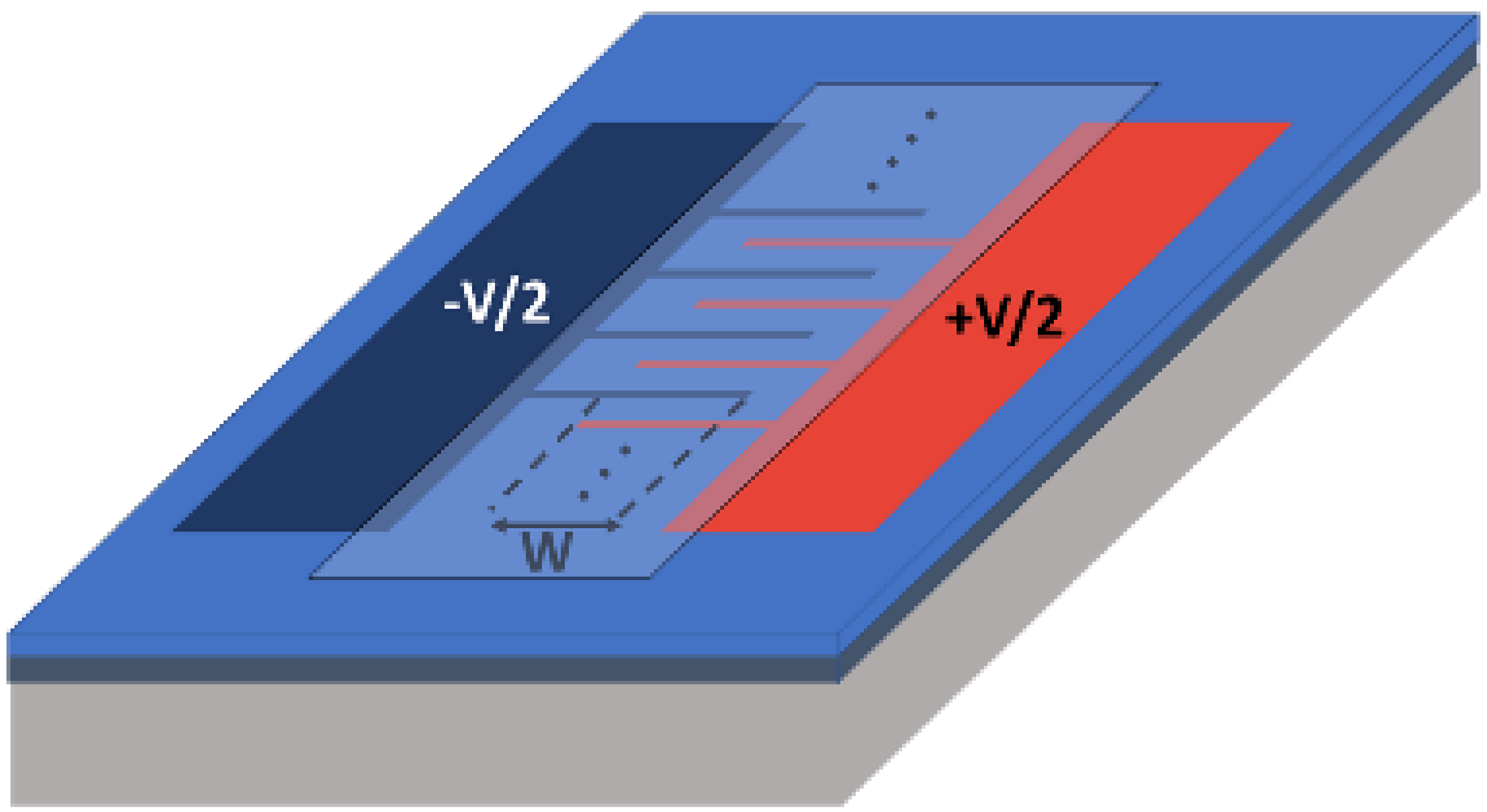
Acoustic wave propagates in a ***vertical*** direction

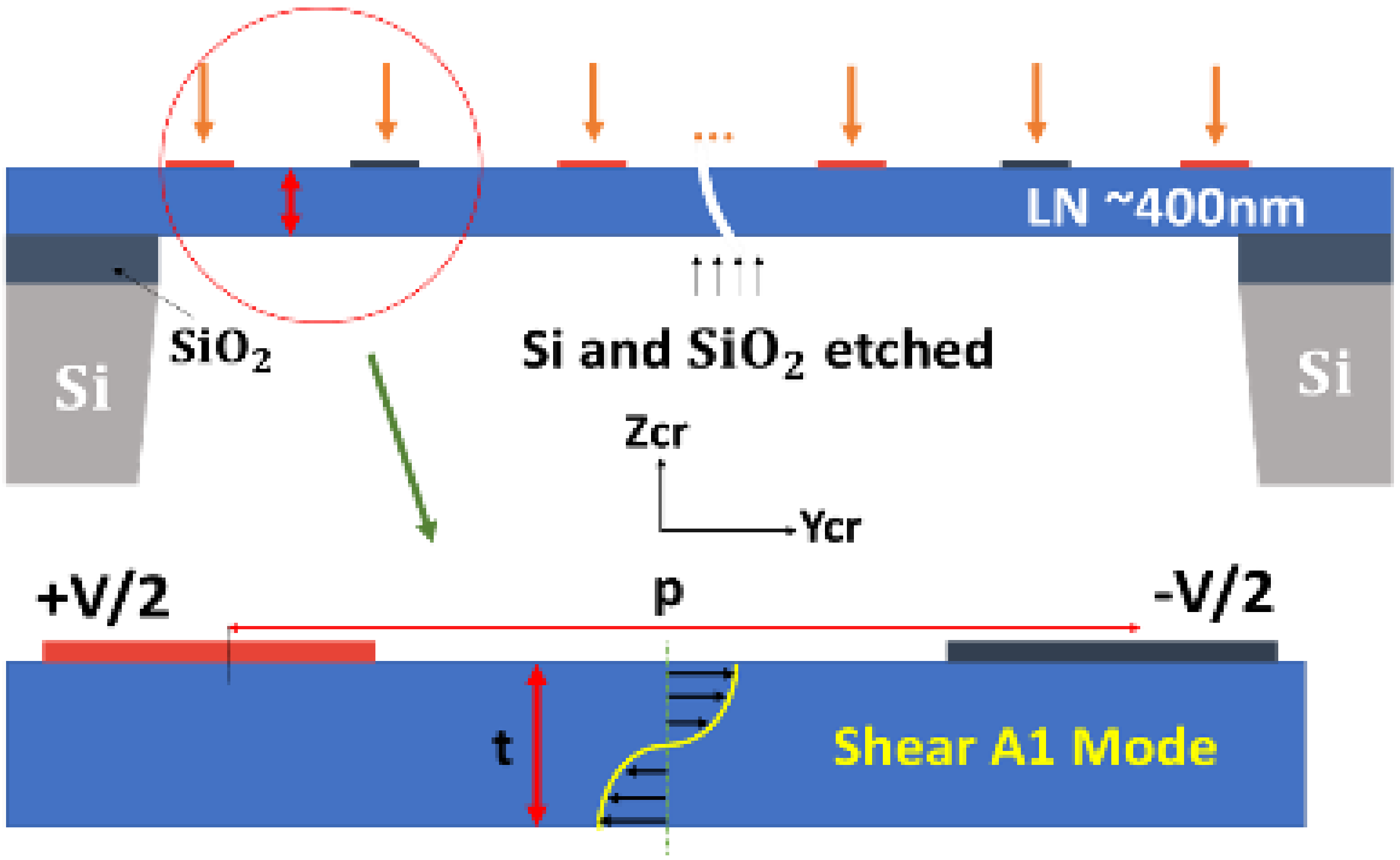


	SAW	TC-SAW	FBAR	BAW – XBAR™
APPLICATIONS	**3G & 4G**	**4G**	**4G**	**4G & 5G**
COST	**Simple, low cost**	**Relatively low cost process**	**Complex, high cost process**	**Leverages standard industry process**
PROCESS STEPS				
PERFORMANCE	**Best performance requires precise process control and improved design**	**Improves temperature stability**	**Low loss and high rejection**	**Best in class performance Ultra-wideband**

RESONANT®

XBAR RESONATOR





- Resonators are the building blocks of filters
  - Properties determine filter characteristics
- Novel resonator structure optimized for new 5G filter requirements
- Uses MEMS process steps to fabricate - no process invention

Concerns/Issues

5G and WiFi Coexistence

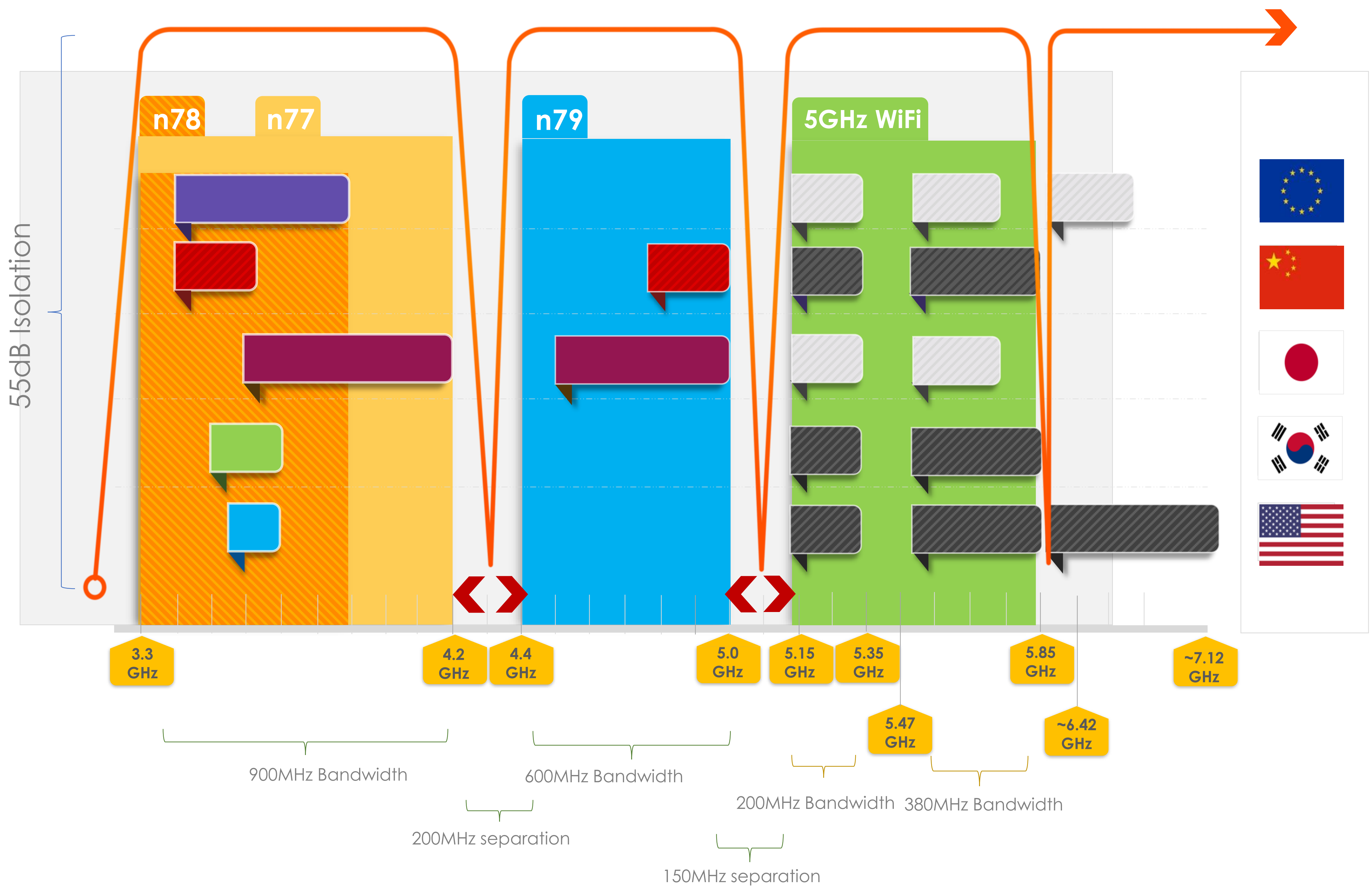
Problem:

- 5G (sub 6GHz) and 5GHz/6GHz WiFi need to operate together in 5G phones
- Massive potential interference problem

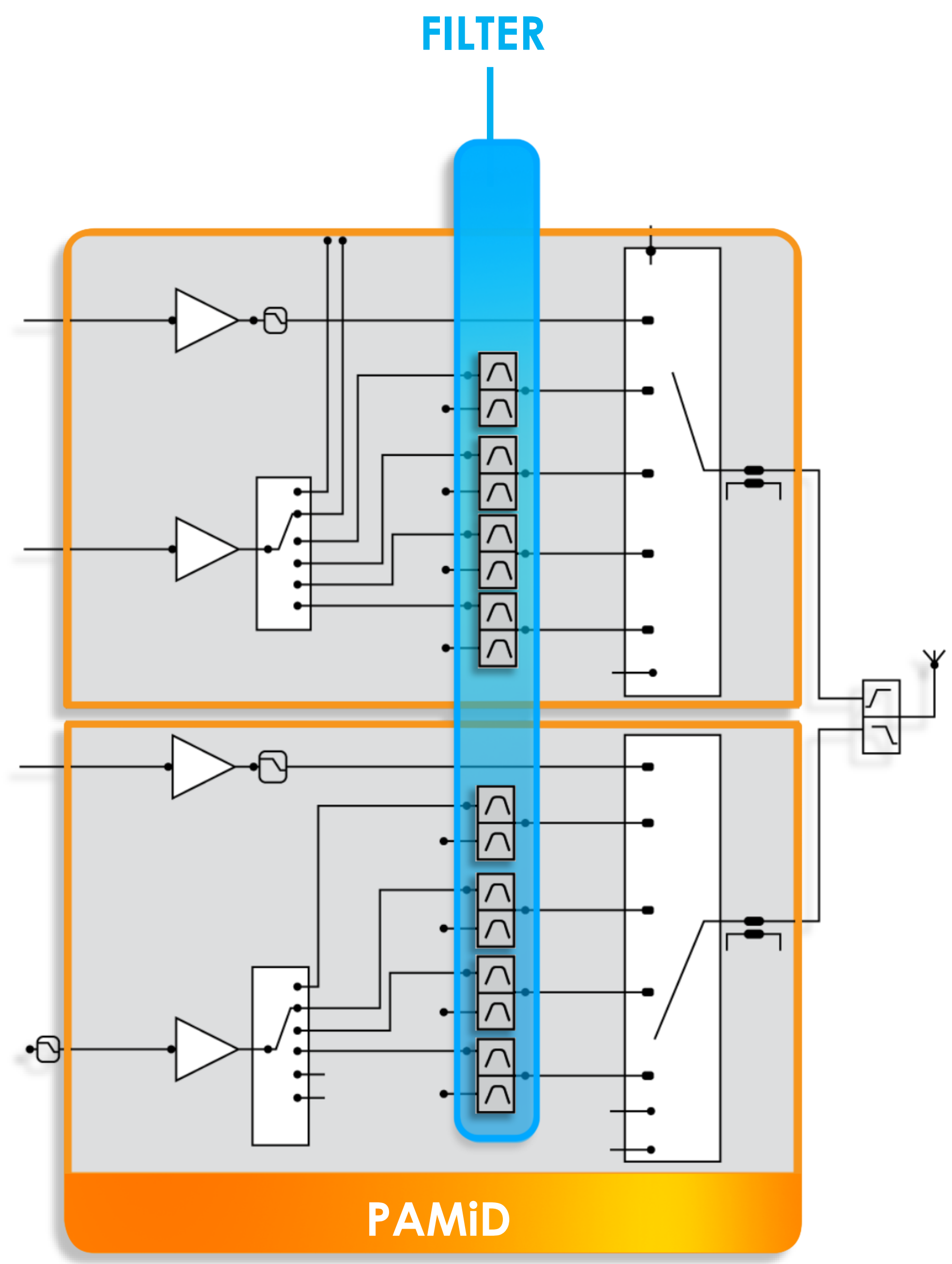
Requirements:

- Large bandwidths
- High isolation/rejection
- Low loss
- High Power
- Small and thin die size

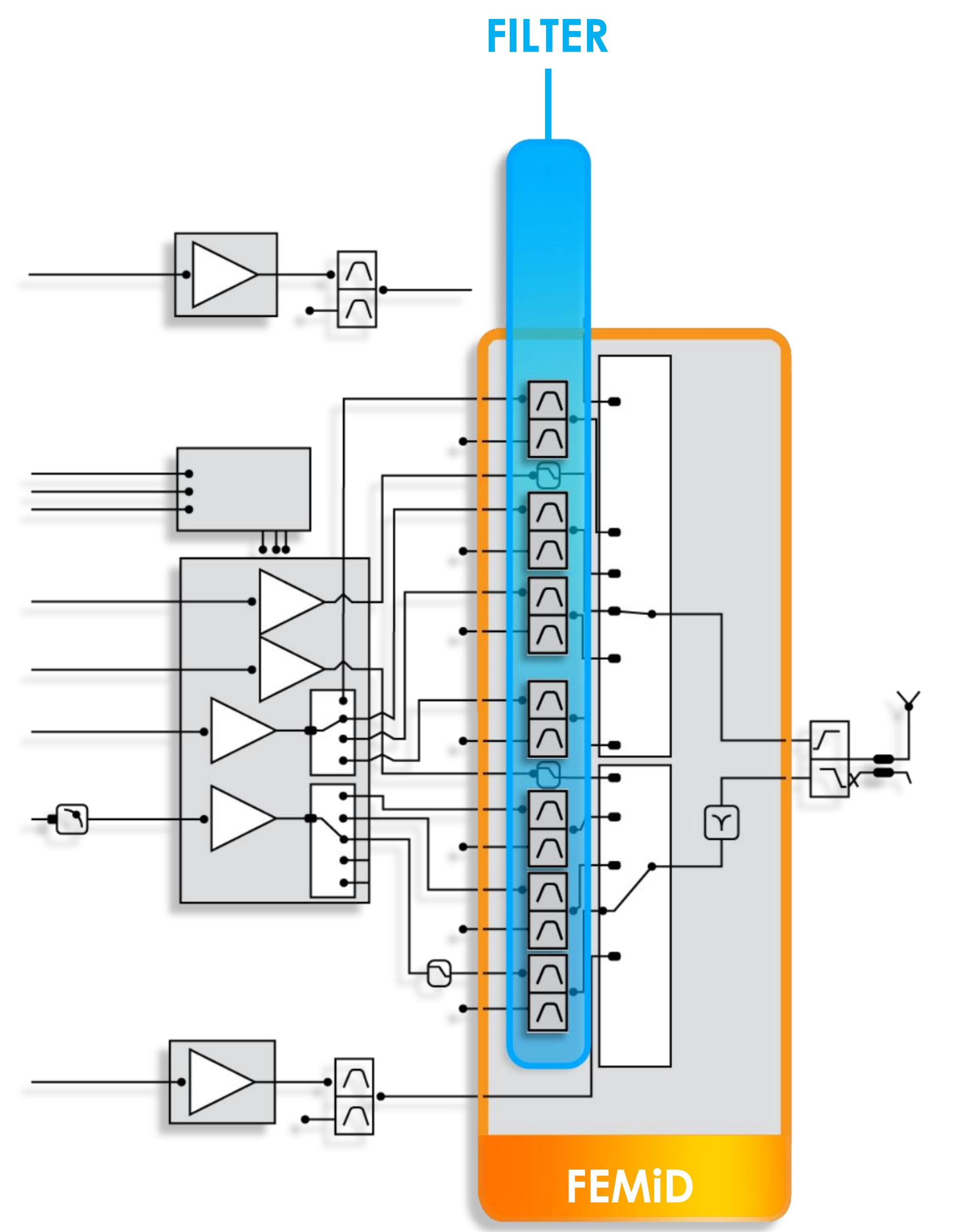
Significantly different from 4G



China-US trade War: PAMiD vs FEMiD



Power Amplifier Module in Duplexer



Front-End Module in Duplexer

Dominant Suppliers:

- Broadcom, Skyworks, QORVO

RFFE architecture change for China

Dominant Suppliers:

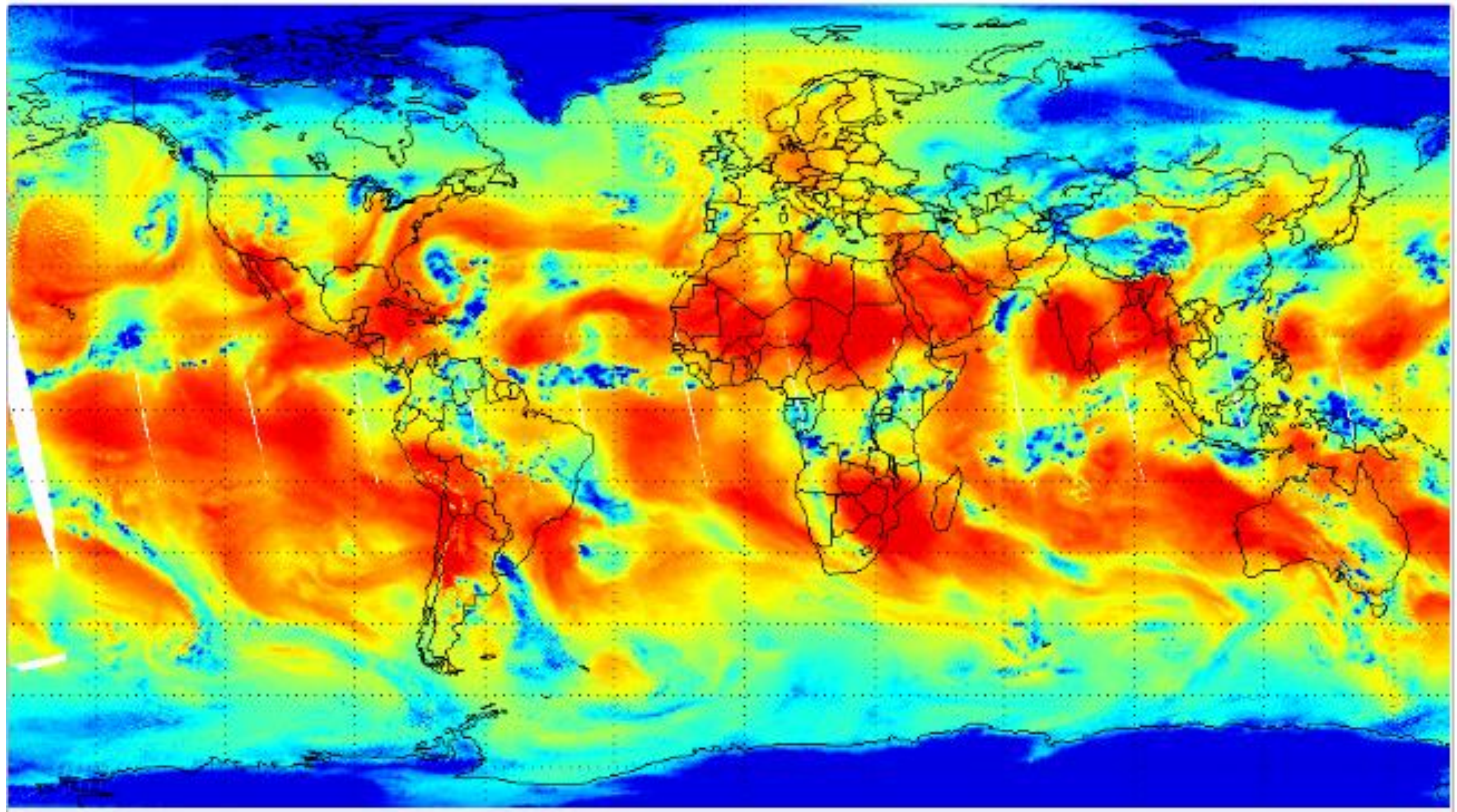
- Murata, RF360, Wisol

CHINA-US TRADE WAR: REDUCED US CONTENT

Component	Mate 20X 5G	Mate 30 series
Assembly	Foxconn, BYD	Foxconn, BYD
CPU	Hisilicon	Hisilicon
Memory	Samsung, Micron	Samsung, Micron, GigaDevice
Camera chip	Sony	Sony, OmniVision
Camera module	Sunny Optical, O-film, Luxvisions	Sunny Optical, O-film, Luxvisions, Q Technology
Camera	Lagan, Sunny Optical	Lagan, Sunny Optical, Kantatsu
Camera motor	Mitsumi, TDK	Mitsumi, TDK
Display	Samsung, BOE	Samsung, LG, BOE
Glass	BIEL, Lense Technology	BIEL, Lense Technology
Touch chips	Goodix, Synaptics	Goodix
Fingerprint reader	Goodix	Goodix
Fingerprint module	O-film, Q Technology	O-film, Q Technology
Connector	Luxshare, Everwin	Luxshare, Everwin
PCB, FPC	Shennan Circuit, WUS	Shennan Circuit, WUS, Zhen Ding
Acoustic	AAC, Goertek	AAC, Goertek
Battery	Sunwoda, Desay, BYD	Sunwoda, Desay
Power management chips	Hisilicon	Hisilicon
RF antenna	Amphenol, Speed	Sunway, Speed
Antenna tuning switch	Qorvo, Skyworks	Mascend, Sony
RF front end	Murata	Murata, Hisilicon
PA	Hisilicon, Qorvo, Skyworks	Hislicon
Baseband chips	Huawei Balong 5000	Kirin 990 5G SoC
RF transmitter/receiver	Hisilicon	Hisilicon
RF chip foundry	WIN Semi	WIN Semi
Wifi chips	Broadcom	Broadcom
Passive components	Murata, Sunlord	Murata, Sunlord

Interference with Weather Satellite Sensors

- Weather Forecasting
  - Weather satellites sense emissions at 23.8GHz to monitor moisture levels in the air
  - Developed after WWII, when it was observed that ~24GHz radar worked best at different times of the year – because of moisture absorption
- Potential Problem
  - US 5G auction of 24GHz spectrum closed in May, 2019
  - Frequency adjacent to moisture emissions
  - Potential interference which would degrade accuracy of moisture levels in the atmosphere
- Mitigation/Solution
  - Not resolved yet
  - Limit 5G power levels at frequencies close to 23.8GHz
  - 5G highly directional at mmWave



An image of water vapor distribution produced with data from the Advanced Technology Microwave Sounder on one of NOAA's polar orbiting weather satellites.

SUMMARY

- 5G Deployments accelerating globally
  - Led by China, Korea, Japan – sub 6GHz
  - US focus on mmWave
    - Propagation challenges
- Innovation required to fulfil the 5G dream
  - Key technologies – MIMO, increased bandwidth, complex modulation, network densification
- Critical Issue
  - Interference
  - Importance of Filters