EDI CON 2018
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RF Front-end Technology and Tradeoffs for 5G mmWave Fixed Wireless Access

Bror Peterson

qorvo
all around you

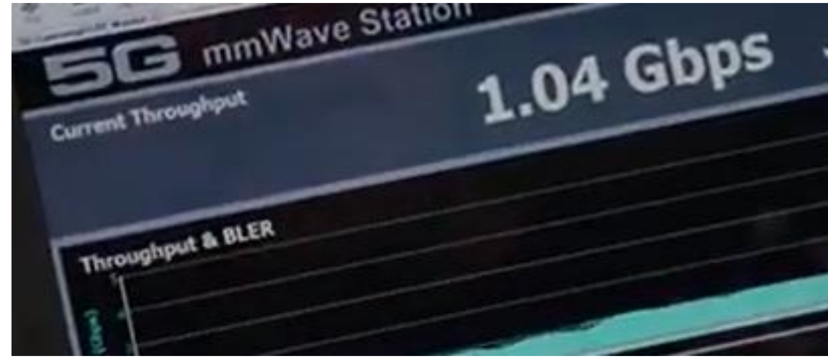
Outline

- Introduction and scope
- The fixed wireless access use case
- Base station architectural trades
- All-digital beamforming architecture
- Hybrid beamforming architecture
- Summary

Introduction

- OEMs are demonstrating second generation mmWave base stations and CPEs in many field trials and preparing for volume production
- Focus will be on cost and performance optimization of third generation equipment
- Two main architectures have been demonstrated
  - Hybrid Beamformed Phrased Array – Nokia, Samsung, Ericsson, Huawei
  - All-digital Beamformed Phased Array – NEC, Huawei
- The front-end semiconductor technology choice for high power base station depends on many things and continues to evolve
- In this presentation I hope to share insight into
  - The fixed wireless access (FWA) use case
  - The two main architectures and some of the challenges for each
  - Highlight the semiconductor technology options and requirements

5G mmWave is Here



Millimeter wave is the key to it all.

Verizon will use 28 GHz and 39 GHz.

So just how far can millimeter wave go?

http://bgr.com/2018/05/22/verizon-5g-gigabit-release-date-coming-soon/

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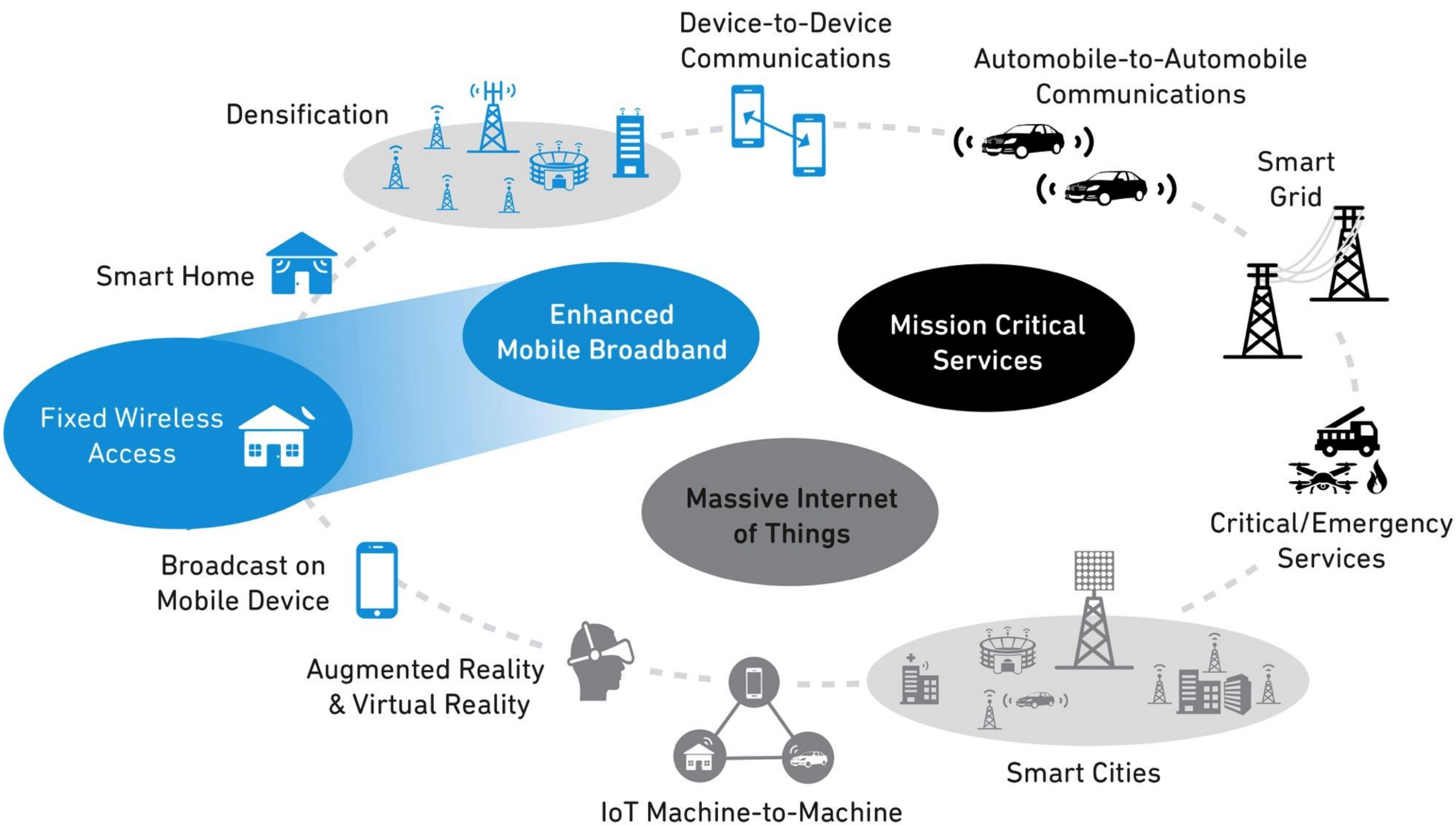
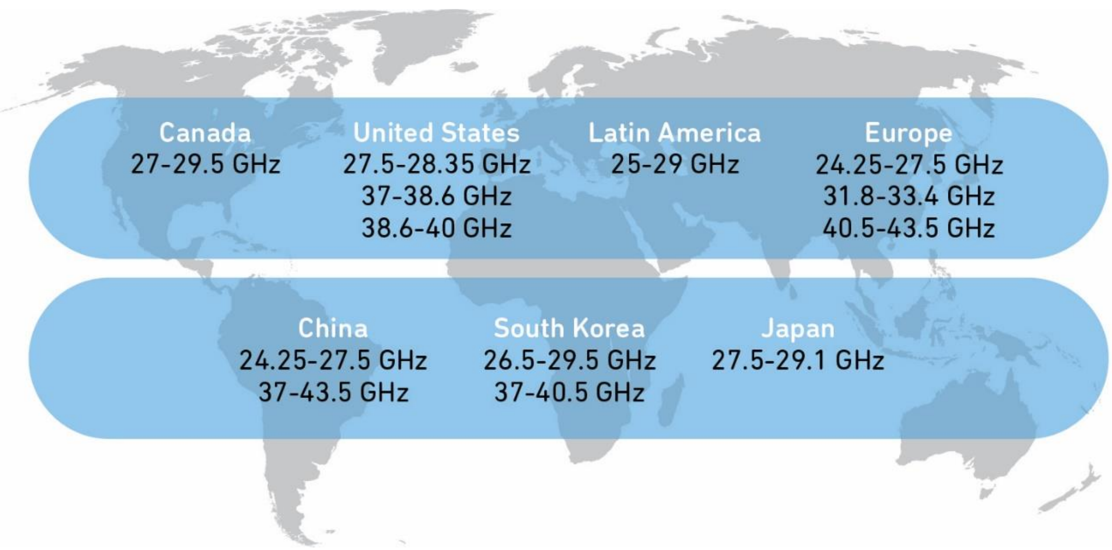
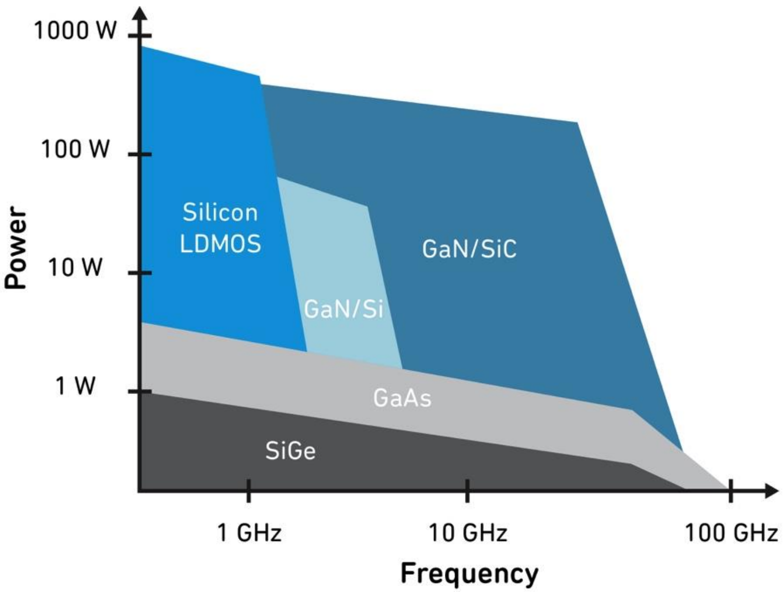
5G as the Platform



- **FWA use case will be the initial driver**
- **Mobile at mmWave sooner than you think – handsets expected 2019**

Frequency Bands for 5G mmWave





- **Clear that 26.5-29.5 GHz and 37-40 GHz bands will be first**
- **24.25-27.5 GHz band will follow**
- **60 GHz bands for FWA deployment are viable but lots of challenges**

Band	Frequency	Mode
N257	26.5-29.5 GHz	TDD
N258	24.25-27.5 GHz	TDD
N259	31.8-33.4 GHz	TDD
N260	37-40 GHz	TDD

Use Cases

- 3GPP has been studying 3 primary use cases at several mmWave bands
  - Indoor hotspot: ISD of 20m, 3m height, 23 dBm RF pave
  - Dense urban: 30m radius, 10m height, 33 dBm RF pave
  - Urban macro: 500m ISD, 25m height, 43 dBm RF pave
- Frequency band: 30 GHz, 45 GHz, and 70 GHz
- New use-case defined specifically for FWA w/high power CPE of 55 dBm

Coverage always comes before capacity!
The market success of mmWave depends on coverage!

TR 38.803: study on new radio access technology: Radio frequency (RF) and co-existence aspects

Pathloss Simulation

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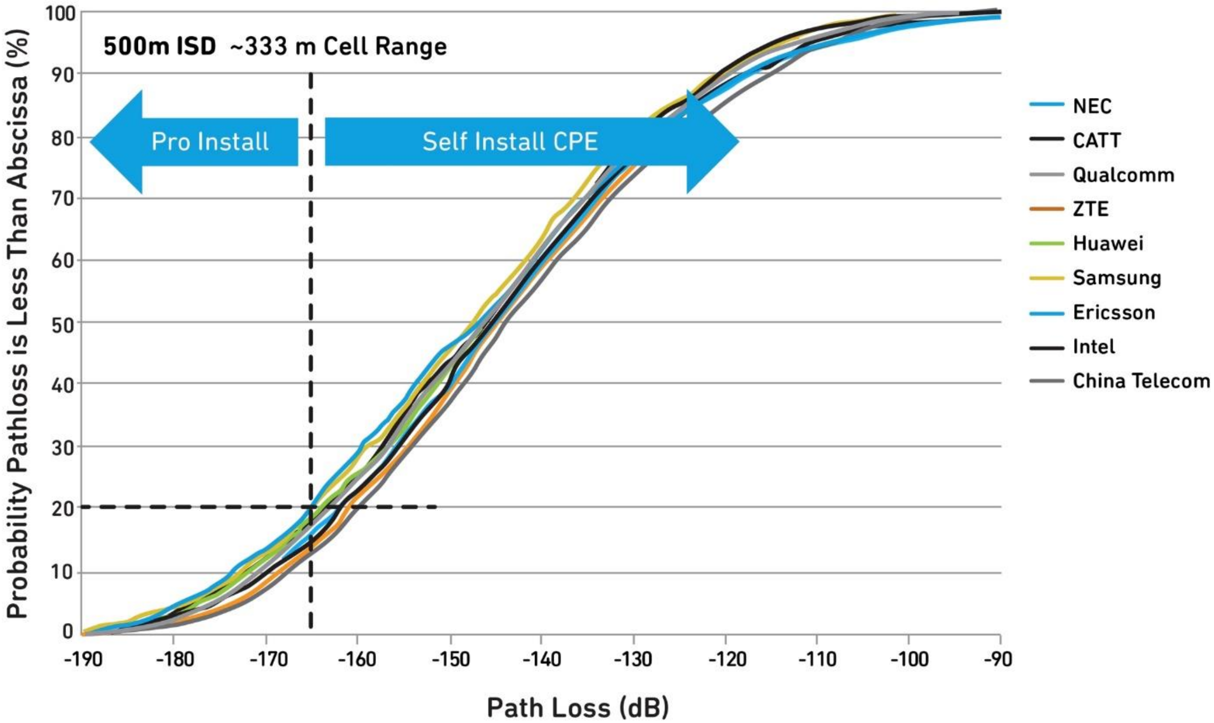
- Pave conducted: 43 dBm
- Antenna array: 8x16 dual-pole
- Outdoor to indoor
  - 80% indoor
  - 20% indoor
- Penetration models
  - 50% high-loss
  - 50% low-loss
- Channel model: UMa

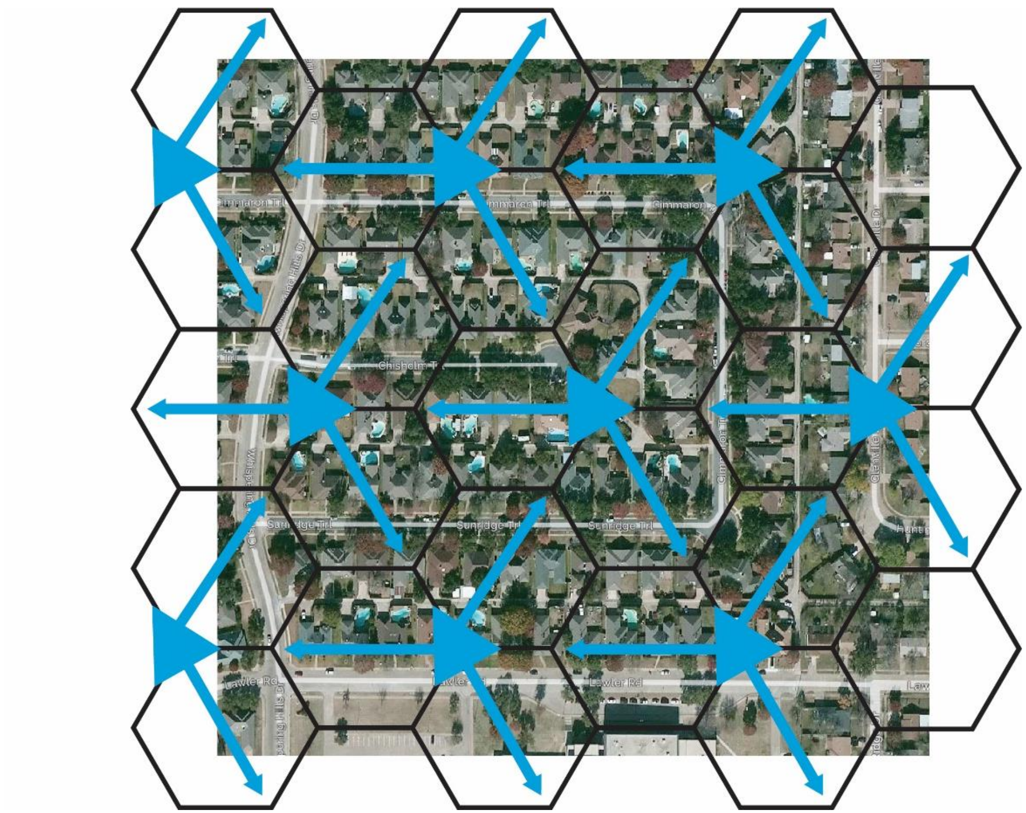
Urban-macro Scenario



- For 80% coverage we need > 165 dB pathloss link budget
- Why 80% and not 99% - assuming that 80% of customers are self-install but carriers can afford up to 20% rooftop deployments (i.e. truck rolls)

Fixed Wireless Access

Is it good business?



Carriers would like at least 1 km ISD to stay out of the core neighborhoods

- Random Dallas Suburb
  - 800 houses/sq-km
  - 500m ISD
  - 9 cell sites
  - 23 sectors
  - ~35 houses/sector
- Capacity per Sector
  - 35 houses/sector
  - 33% take rate
  - 5x oversubscription
  - 1 Gbps service/user
  - Capacity ~ 3 GbpsBTS
- Parameters
  - 800 MHz BW
  - QAM16 w LDPC: 3 bps/Hz
  - 2 spatial streams/layers
  - Capacity ~4.8 Gbps
- Business Case:
  - 33% take rate
  - $100/month for 1 Gbps SLA
  - $14K/sector/year
  - $280K/sq-km/year

What EIRP is Needed to Close The Link?

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DL link budget supporting ~200 Mbps to CPE on cell edge

BTS Tx	
Conducted Power	43 dBm
Array Size	64 elements
Beamforming Gain	18 dB
Single Element Gain	5 dBi
Tx EIRP	66 dBm

CPE Rx	
Noise Figure	6 dB
Array Size	16 elements
Beamforming Gain	12 dB
Single Element Gain	5 dBi

DL Link Budget	
Tx EIRP	66 dBm
Pathloss	165 dB
Rx BF+Ant Gain	17 dB
Rx Signal	-82 dBm
Bandwidth	200 MHz
Thermal Noise Floor	-91 dBm
Rx NF	6 dB
Required SNR	1 dB
Min Detectable Sig	-84 dBm
Link Margin	2 dB

The FCC has allowed 75 dBm/100 MHz of EIRP – can we get there?

FCC Part 30.202 Power Limits

Equipment Class	Power (EIRP)
Base Station	75 dBm/100 MHz
Mobile	43 dBm
Transportable Station	55 dBm

Closing the link at 500 meter ISD will require base stations to have at least 65dBm EIRP – regulatory limit not the problem

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Quick Summary

- Fixed wireless access is here
- 28 GHz and 39 GHz are lead bands
- >165 dB pathloss budget
- >65 dBm EIRP at BTS but carriers want more
- Regulatory limits not an issue

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Base Station Architectural Trades

- We have established that we need 65 dBm average EIRP
- How do we architect a system that is:
  - Low cost
  - Allows passive cooling all-tower top electronics
- Some of the major trades that impact PA requirements:
  - How big does my antenna array need to be?
  - How many active T/R chains do I need?
  - Do we really need 2-D beamforming?
  - Are separate Tx and Rx arrays okay?
  - Can we use separate arrays for each polarization?
  - Do I need hybrid beamforming or is all-digital BF possible w/todays components?
  - Do we need III-V front-ends or with enough elements can we use SiGe front-ends and if so, does it minimize cost, complexity, Pdiss?
  - Many more…

Do We Need 2-D Beam Steering?

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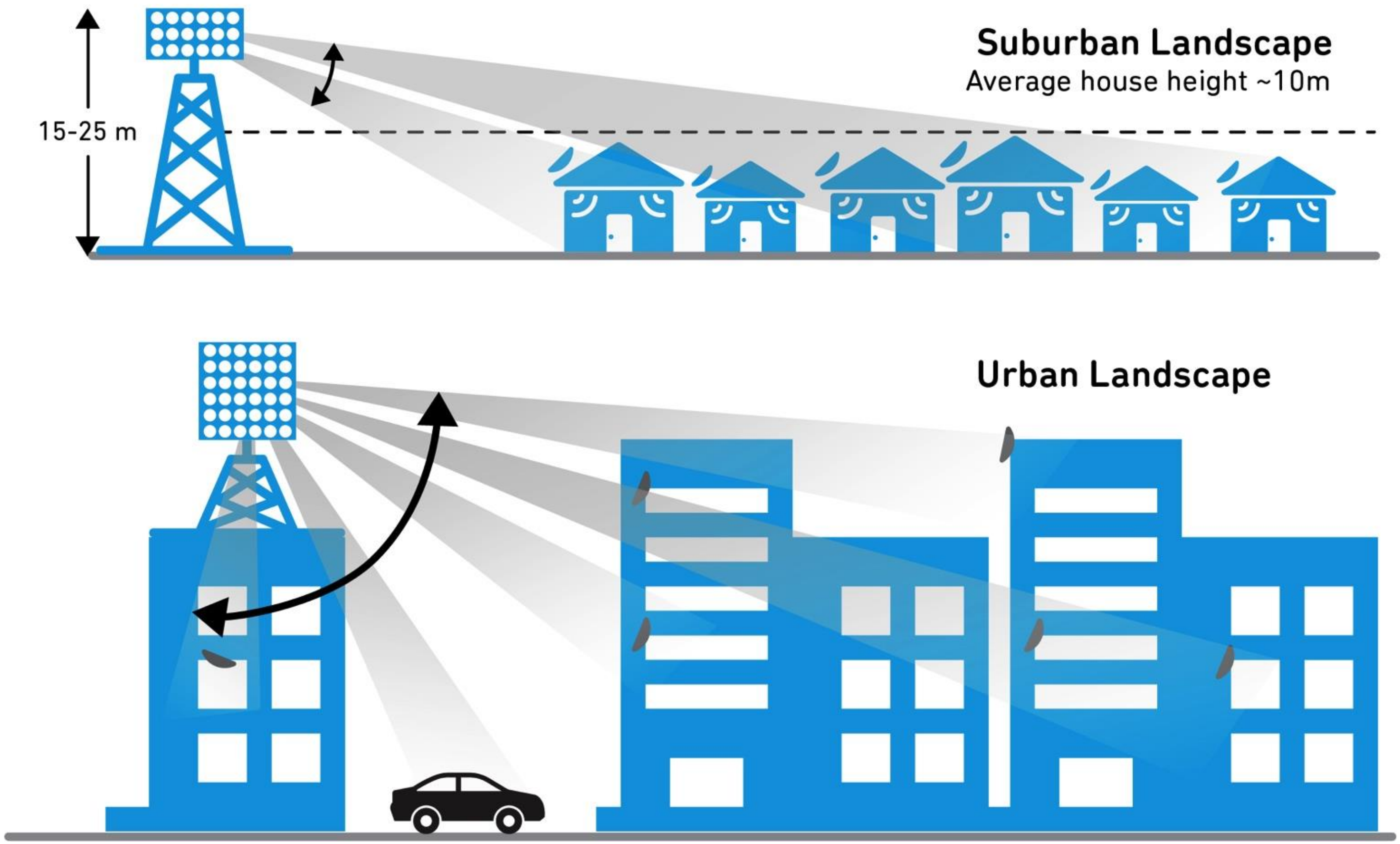

- Most macro-BTSs today used fixed elevation patterns – for best coverage
- FWA use case does not necessarily require elevation beam steering
- 2-D beam steering (e.g. FD-MIMO) was introduced for capacity but we need to focus first on coverage

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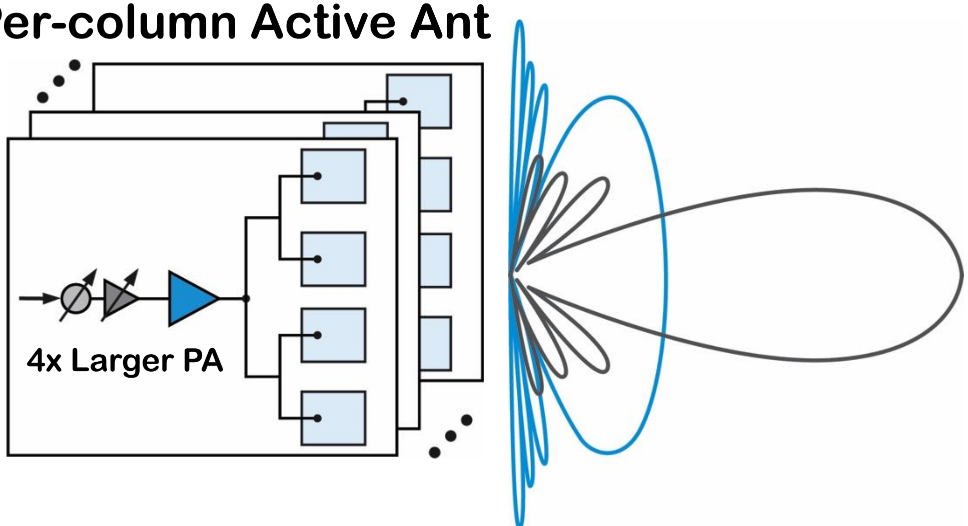
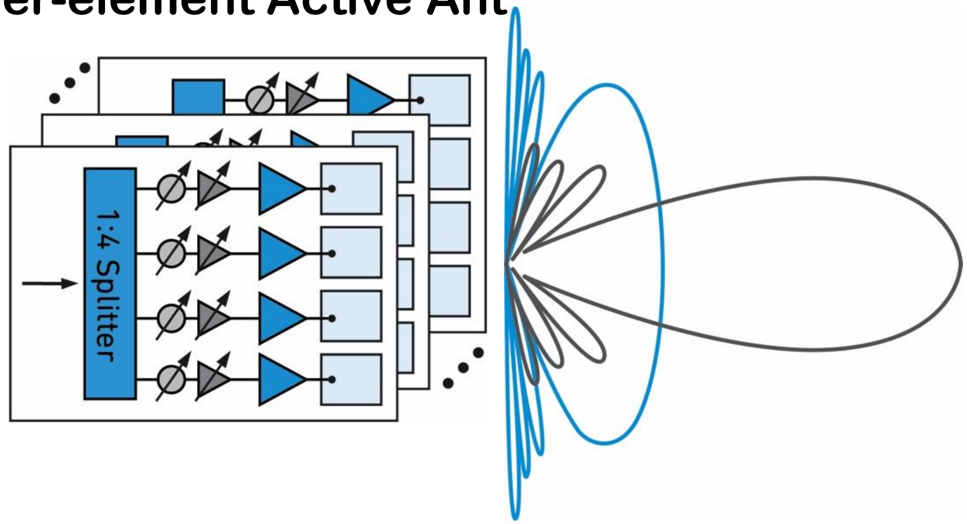
Do We Need 2-D Beam Steering?

Why is this important to the system?

Per-column Active Ant



Per-element Active Ant



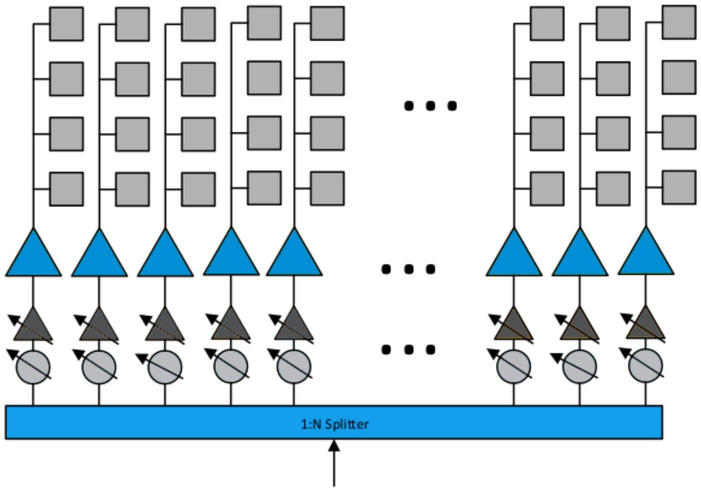
Half power beam-width: 102°/N
Linear array gain: ~10log(N)+5 dBi

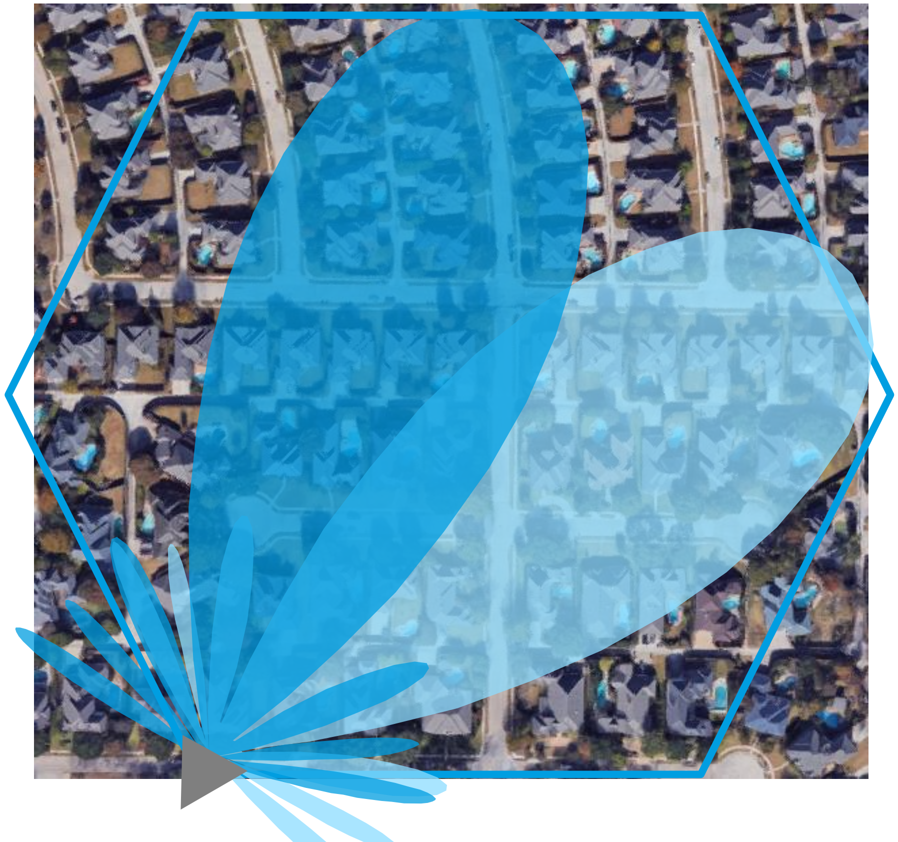
Array	Beamwidth	Gain (dBi)
Single Element	102	5
Dual Elements	51	8
4-Elements	26	11
8-Elements	13	12.75

- Both achieve the same gain
- Per-column approach
  - Fewer RF components
  - N-times larger PA
  - Antenna feed loss
  - Fixed elevation pattern
- Per-element approach
  - N-times more components
  - N-times smaller PAs
  - Elevation beam steering

Do We Need 1-D Beam Steering?

- Azimuthal beam steering is definitely needed
  - Improves EIRP and G/T
  - Minimizes inter-cell interference
  - Supports MU-MIMO (multiple spatial layers)
- How large to make the array?
  - Wide range of answers
  - Trade off between
    - PA size
    - Calibration complexities
    - Cost/complexity of design





General consensus is that array size needs to be at least 8 columns (e.g. <13° 3dBBW, +/-60° AZ steering)

Do We Need Integrated T/R?

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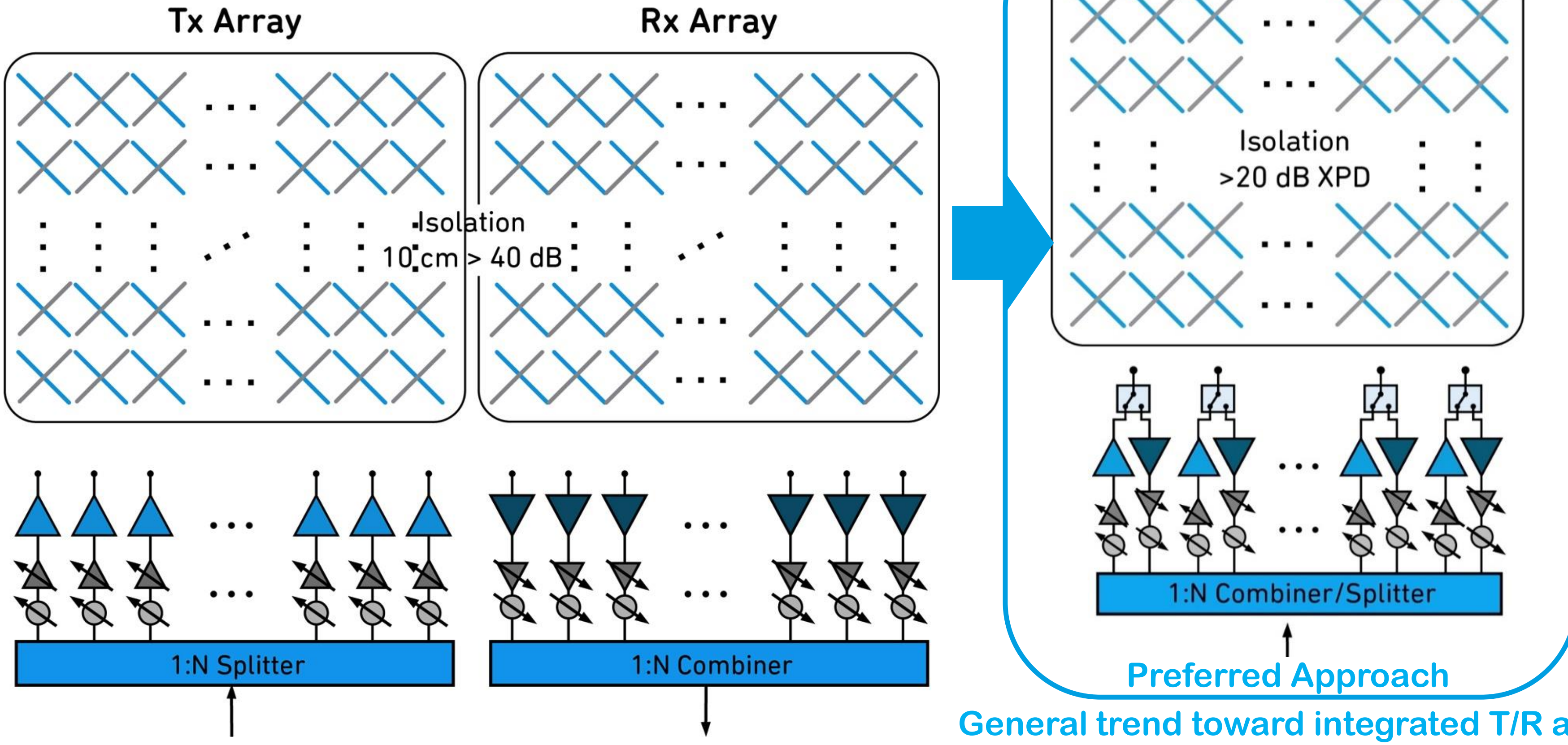
Many of the 5G mmWave prototypes we have seen today use separate Tx and Rx arrays, why?

- TR switch is lossy and power handling/linearity limited
- Better NF and EIRP with separate arrays
- Independently scale to balance UL and DL requirements

Eg:
- 39 GHz 8x16 array
- 128 elements
- Size (H/W): 4cm x 6cm

SW Loss:
- >0.8 dB @28 GHz
- >1.0 dB @39 GHz



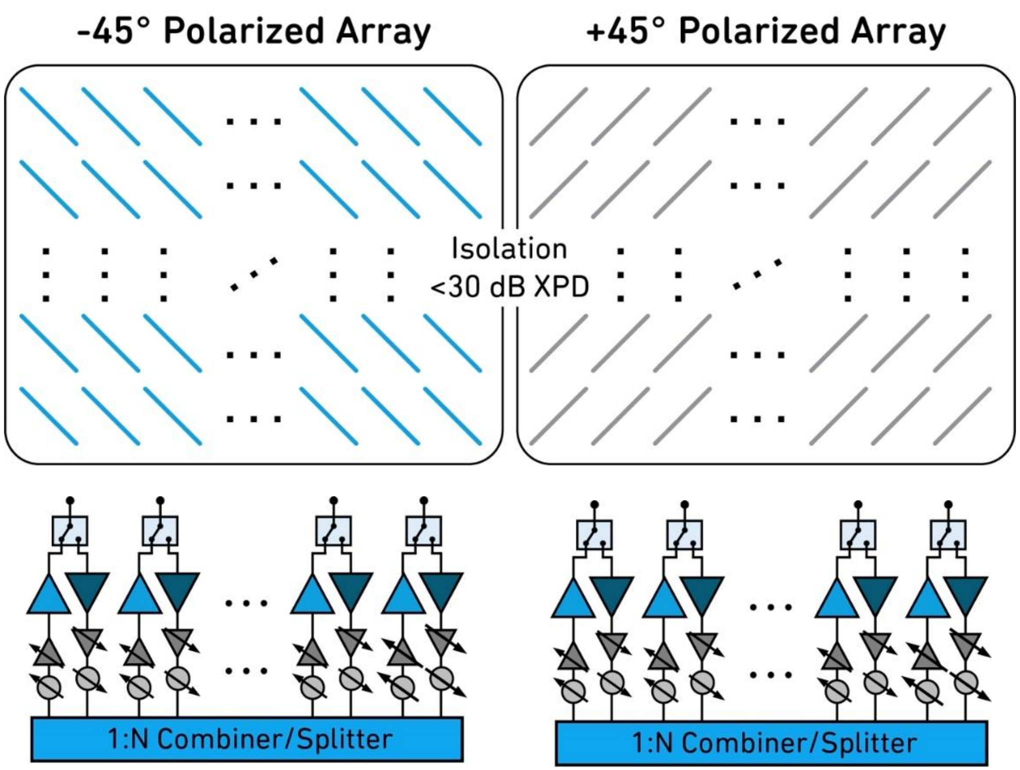
General trend toward integrated T/R array

Do We Need Dual-Polorization?

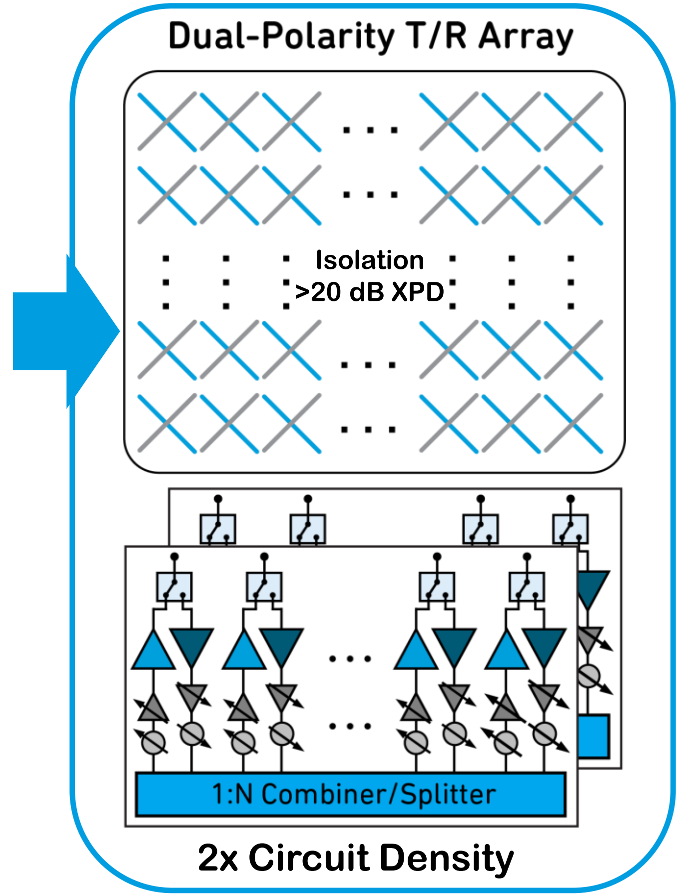
Many of the 5G mmWave prototypes we have seen today use separate arrays for polarization

- Polarization is quickly lost for nLOS and NLOS environments
- Dual-polarization is needed for diversity, and
- In good conditions, provides isolation for X-pol MIMO

Eg:
- 39 GHz 8x16 array
- 128 elements
- Size (H/W): 4 cm x 6 cm



General trend toward dual-pol array



Preferred Approach

Reciprocity Must be the Reason

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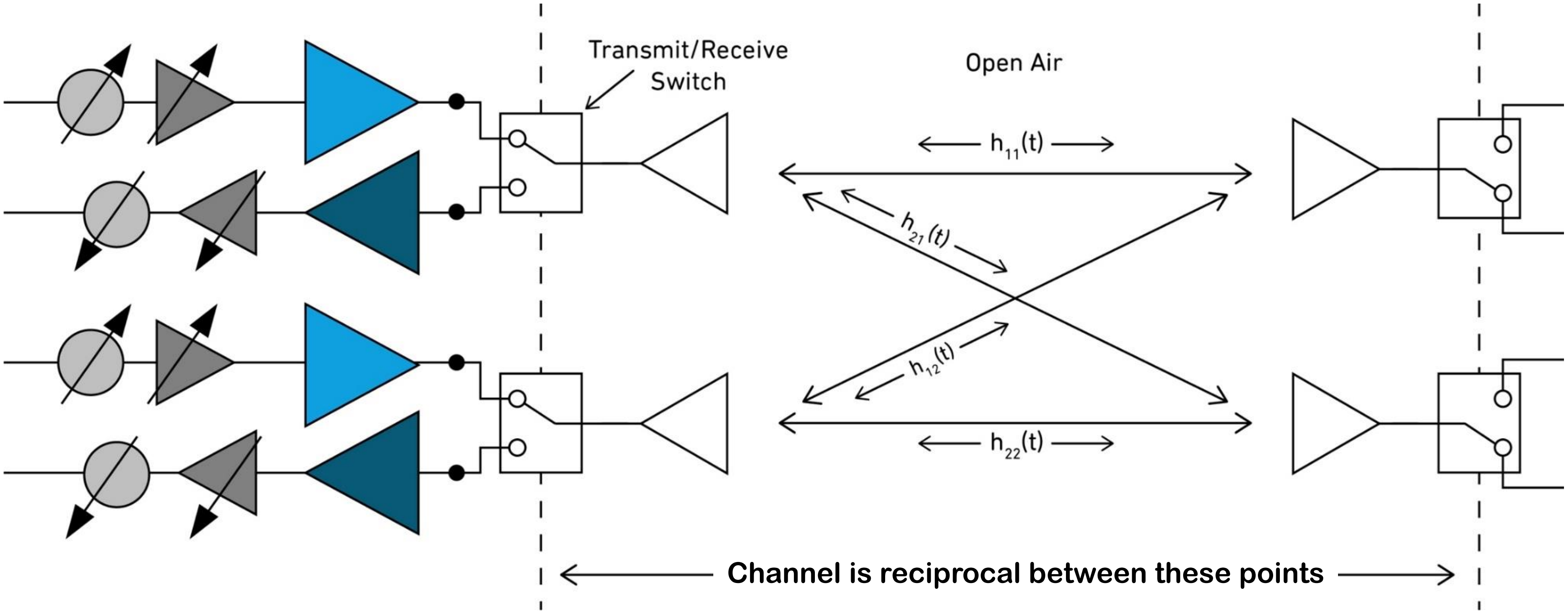

- Sub 6 GHz TDD FD-MIMO uses uplink channel information to form the downlink beamforming weights
  - Low signaling overhead
  - Requires precise Tx and Rx calibration
- Initially mmWave systems will use hundreds of pre-stored spot beams
- Over-time there is a desire to support more adaptive transparent beamforming like sub 6 GHz systems
- Not required day-one for FWA but important for mobile use case

Quick Summary

- 2-D beamforming is not required for FWA
- At least 8 columns in array – can be more
- T/R is preferred
- Dual-pole is preferred

} 4x integration density – will drive advanced packaging solutions

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Can I Stay with My All-Digital BF Architecture?

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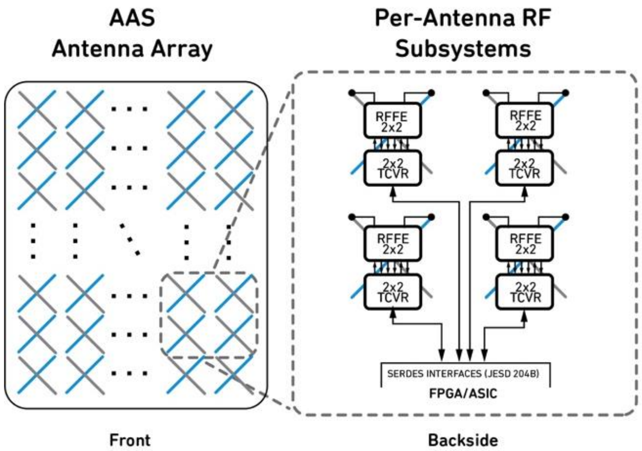
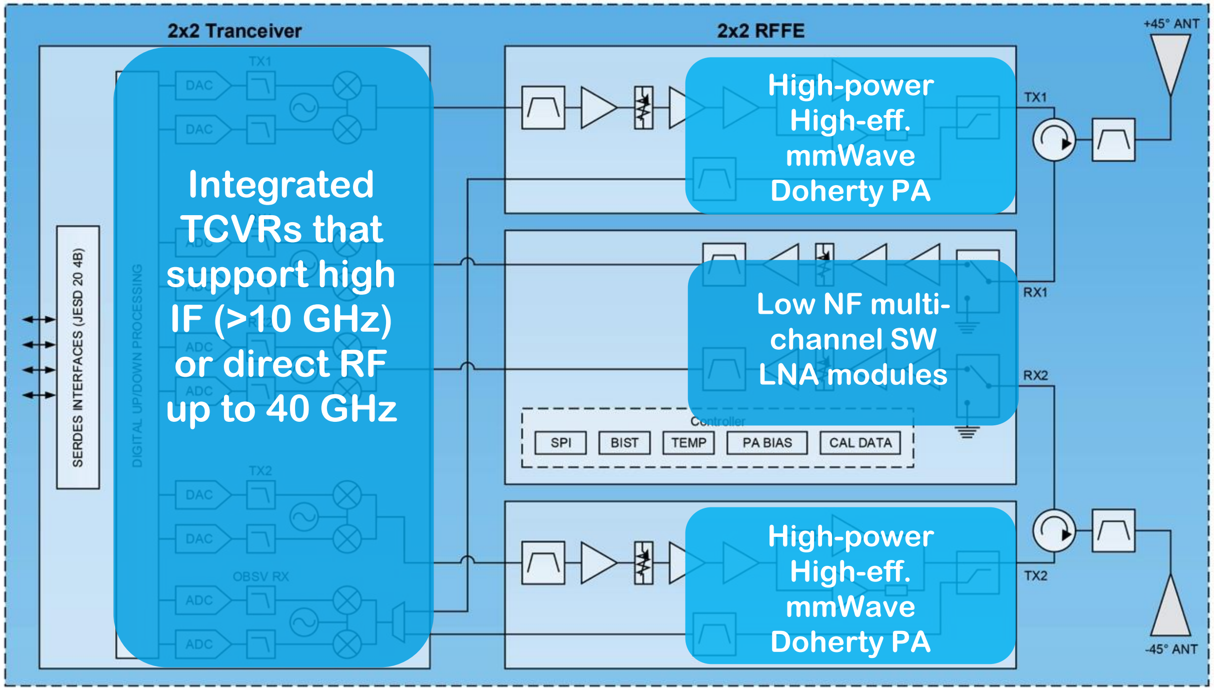
Can we extend current mass-MIMO architecture by bolting on a high power mmWave front-end and reuse all-digital beamforming algorithms – very desirable long term



Detailed Block Diagram of 2x2 RF Frontend Modules



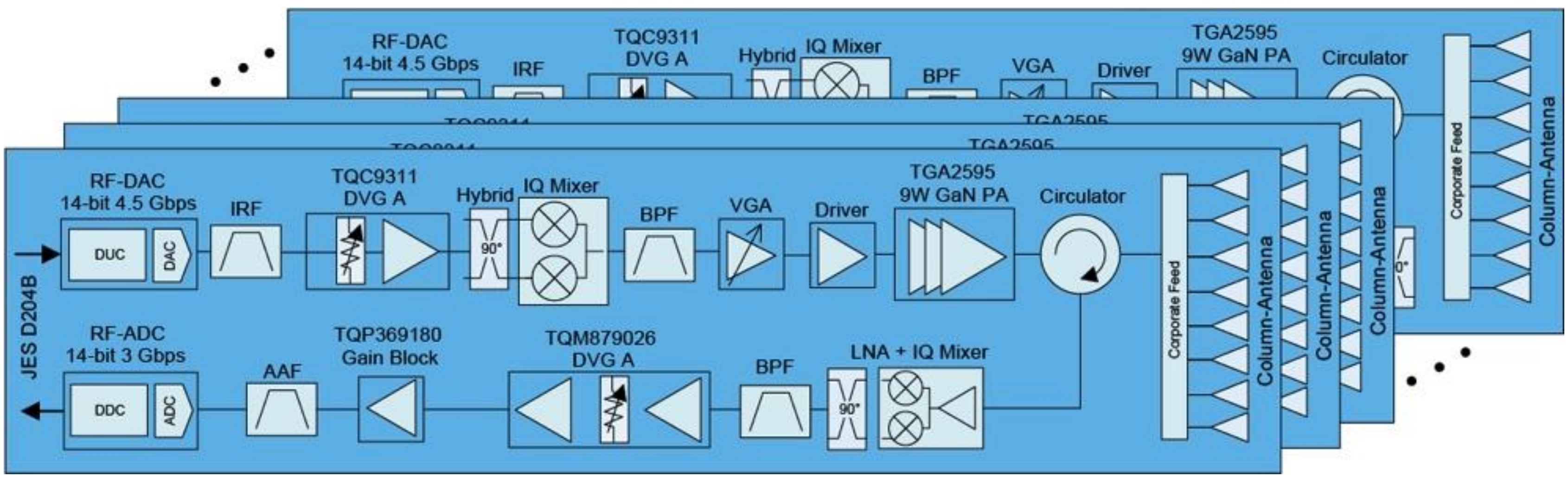
- Generally assumed by most that power dissipation is too high
- What components need to be developed to enable this?

High Power 28 GHz All-Digital Beamforming/MIMO

Todays off-the-shelf components

- What is the power consumption of an all digital BF architecture that achieves an average EIRP of >65 dBm?
- Care was taken to use only components that are available today

RF System Block Diagram



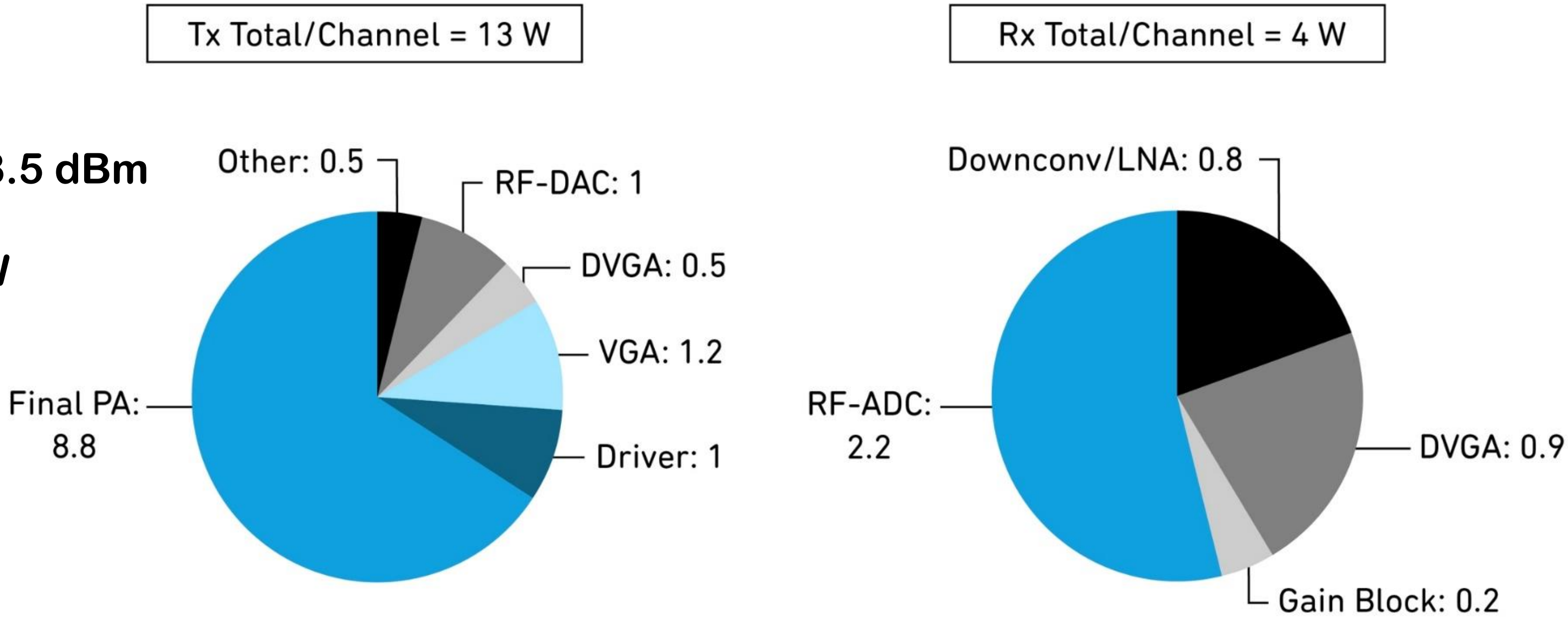
Key requirements

- >65 dBm average-EIRP
- >800 MHz bandwidth

High Power 28 GHz All-Digital Beamforming/MIMO

Today’s off the shelf components

PA Power: 28.5 dBm
PA Eff: 8%
Pdc/PA: 8.8W



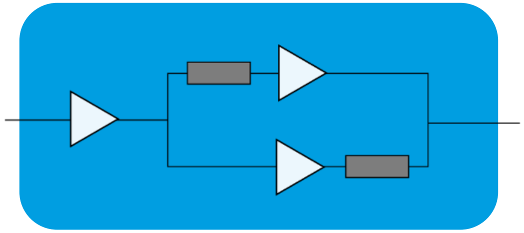
- Total power dissipation (P_{DISS}), at 80% transmit duty cycle for all 16-slats, will be 167 W/polarization and a dual-polarized system would require 334 W
- For all outdoor tower-top electronics where passive cooling is required, it is challenging to thermally manage more than 200 W from the RF subsystem

Todays linear PA technology is prohibiting all-digital BF solutions

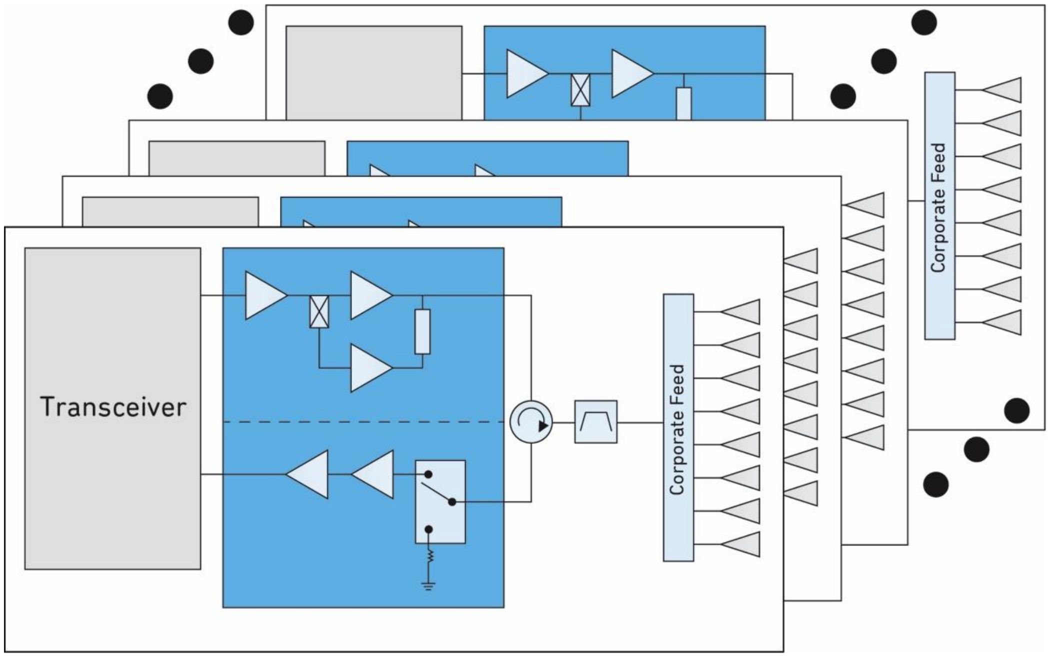
High Power 28 GHz All-Digital Beamforming/MIMO

Next-generation front-end components

High Power and Efficiency Multi-Stage Doherty PA



Pave: 1-2W
PAE: >20% @ 8 dB BO



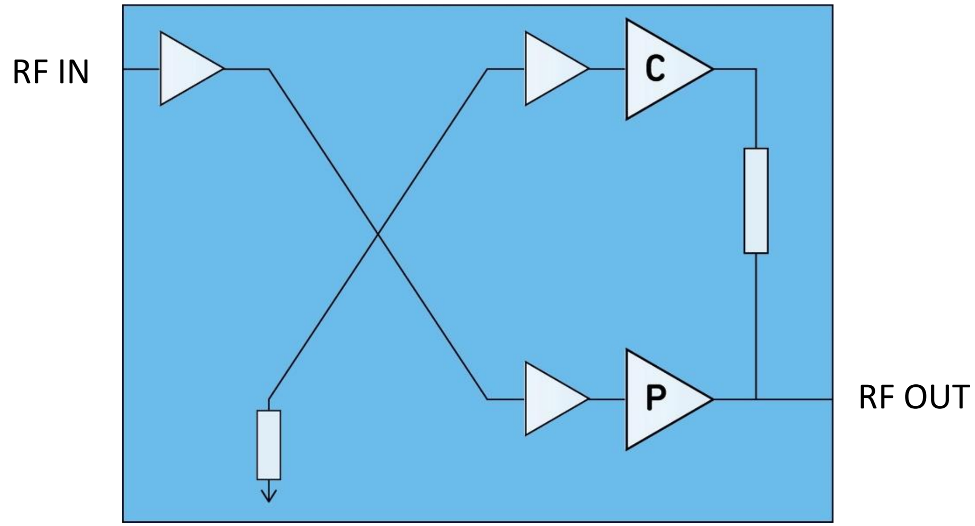
- Doherty PA is a key enabler towards all-digital mmWave BTS
- DPD is a concern – however
  - Sub 6 GHz mass-MIMO systems today are already doing 200 MHz – not a big leap to 400 MHz
  - Loose ACPR requirement of 27.5 dBc @ 28 GHz make the problem much easier than sub 6 GHz LTE

Family of High-Power High-Efficiency mmWave PAs

28 GHz 10W Psat Doherty GaN15 PA module

Product Features

- Integrated driver plus dual stage Doherty final
- Frequency: 27.5-29.5 GHz
- Power: 10W P_{SAT} (40 dBm)
- Pave: 33 dBm at 4% EVM
- PAE target 24% (at 33 dBm)
- 24 dB linear gain
- QGaN15 on SiC process
- 50 Ω in/out
- Air cavity EHS-L (embedded heat sink laminate)
- Some predistortion needed for best efficiency



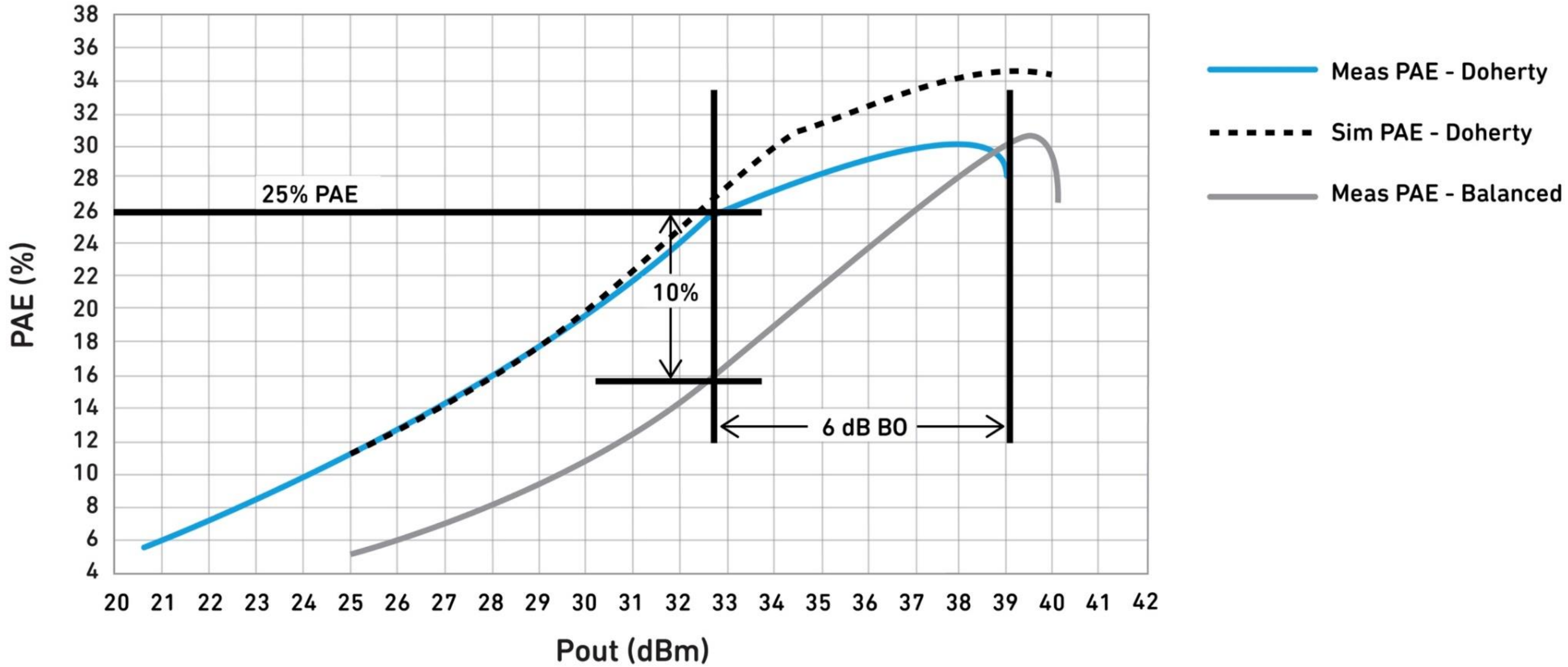
6.25 x 4.5 mm

Parameter	Value
Operational frequency range	27.5-29.5 GHz
Supply voltage	28 V
Gain	24 dB
P_{SAT}	10 W
Min PAE at 33 dBm	>20%

Status: Select Sampling

QPA2810 Measurement Results

28 GHz Doherty GaN15 PA module – untuned preliminary measurements



By replacing the linear GaN PA with a high-efficiency Doherty GaN PA we can reduce power consumption from 334W to less than 180W

Quick Summary

- Seems very desirable to extend current mass-MIMO architecture to mmWave – reuse the platforms
- With todays RF components PA power consumption is too high
- High-power Doherty PAs can change the equation
- Lower power ADC/DACs on the way w/28nm and 14nm CMOS nodes

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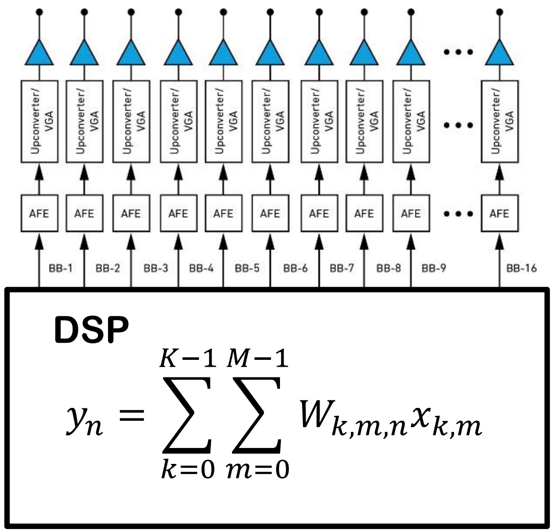
Hybrid Beamforming Architecture

- Hybrid beamforming has emerged as an enabling technology and potentially disruptive
- It's important to understand:
  - What am I giving up compared to all-digital beamforming approach?
  - What is the optimum number of elements?
  - What semiconductor technology makes sense?
  - Does all SiGe solution really scale to high EIRP?
  - Or will the solutions be a combination of SiGe BF + III-V front-end components?
  - What III-V technology makes sense? GaAs, GaN?
  - Many more…

Hybrid BF vs Digital BF

It has been shown theoretically that hybrid BF can achieve the same sum-rate capacity as an all-digital BF system under certain conditions

All-Digital BF

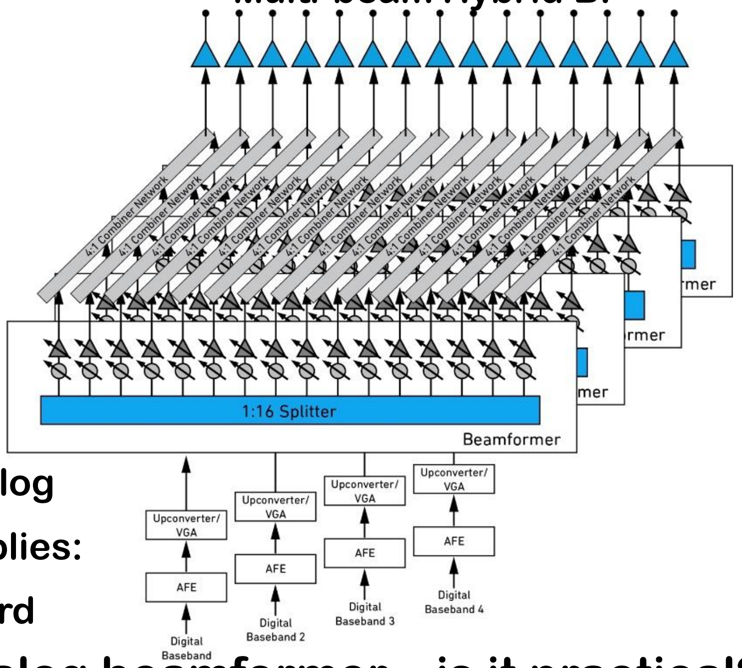


$$y_n = \sum_{k=0}^{K-1} \sum_{m=0}^{M-1} W_{k,m,n} x_{k,m}$$

Digital Multiplies: Easy

Shared Aperture (Fully-connected)

Multi-beam Hybrid BF



Analog Multiplies: Hard

- **Results in a very complex multi-beam analog beamformer – is it practical?**

- References:
- Molisch et al. Hybrid Beamforming for Massive MIMO – A Survey
- Heath et al. An Overview of Sig Proc Techniques for mmWave MIMO Systems
- Han et al. Large-scale Ant Systems with Hybrid Analog and Digital Beamforming for mmWave 5G

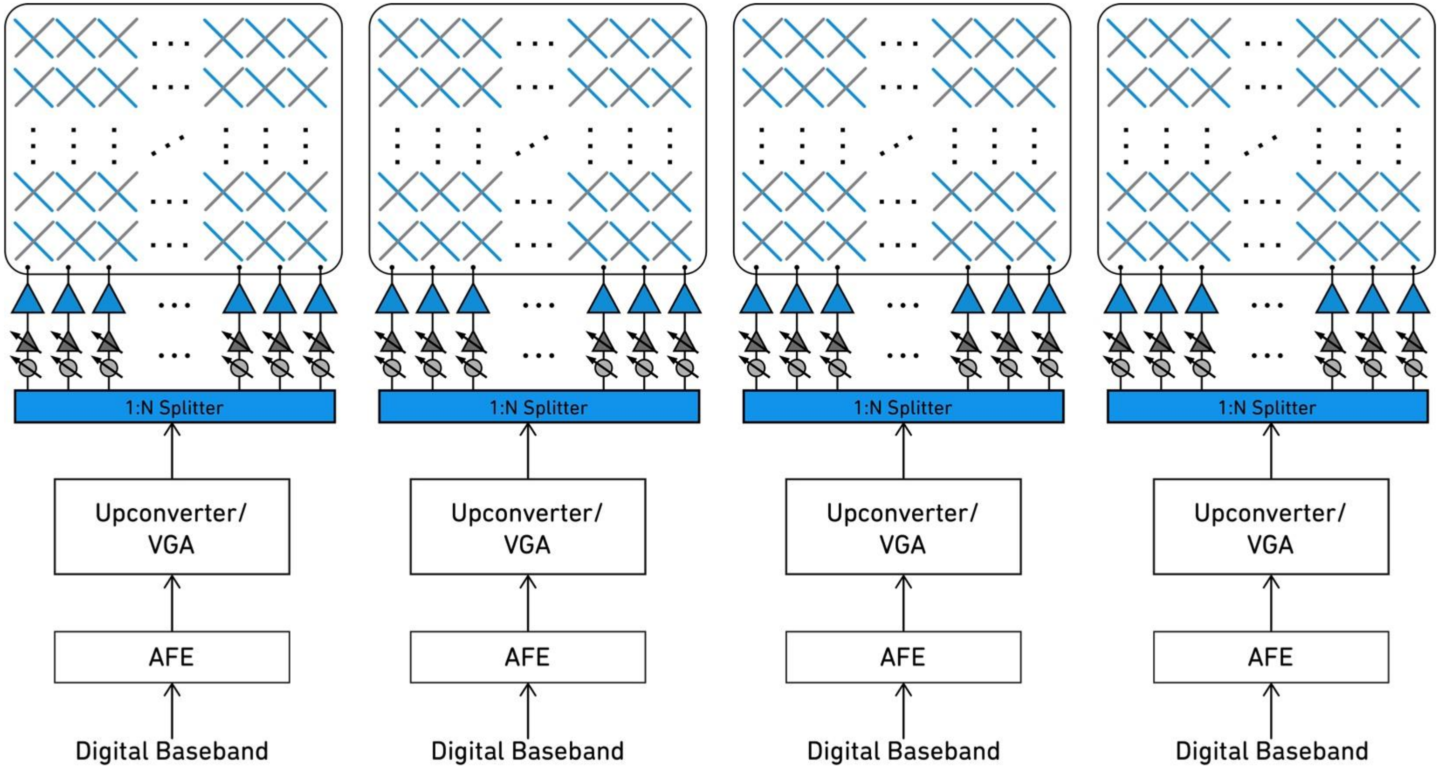
This type of multi-beam analog beamforming is currently too complex and a divide-and-conquer approach is needed to make practical

Multi-Beam vs Paneled Single Beam

The "fully connected" hybrid-BF is far too complex

- Divide and conquer w/separate subarray panels

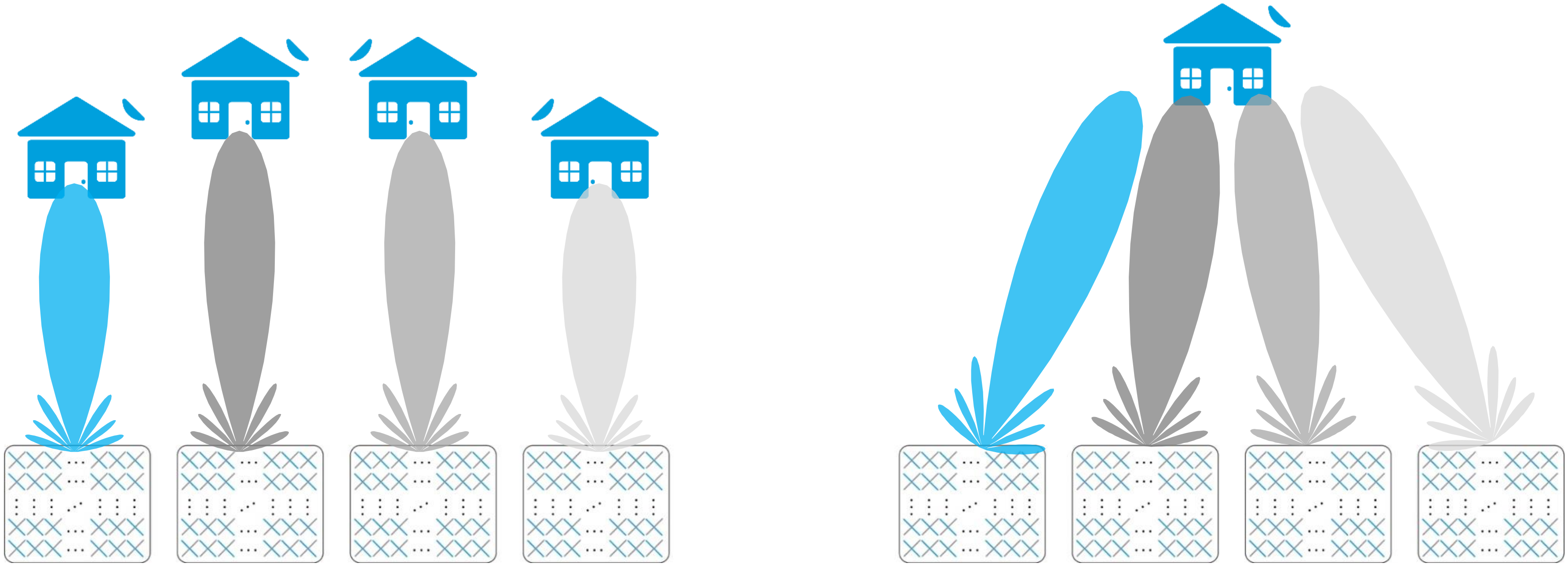
Paneled (Tiled) Single-Beam Sub-Arrays



- Same number of phase shifters and VGAs, but…
- M-times as many PAs, LNAs, SWs – good trade?
- Does allow for smaller PAs – a good thing for Si-based PAs

Paneled (Tiled) Hybrid BF Approach

Panels can be tiled together for higher EIRP or used independently for more capacity



Multiple Spatial Streams for Capacity

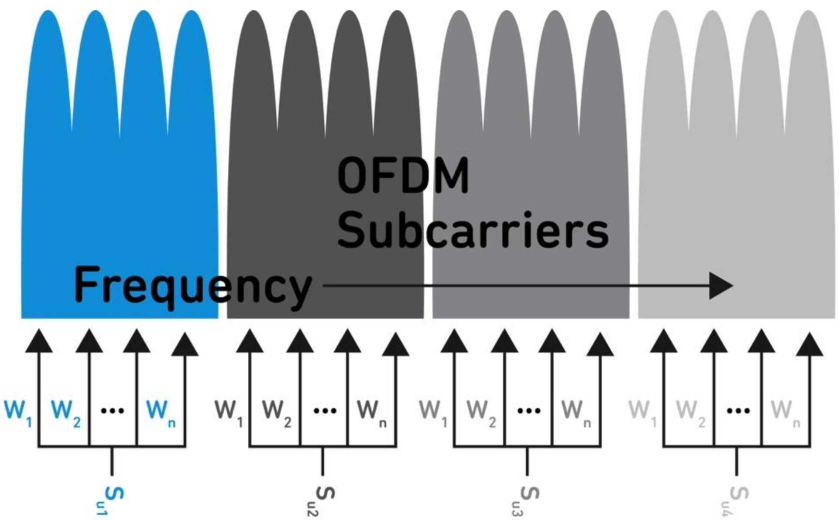
Analog + Dig BF for Range

- Scalable plug-and-play building block
- Will require good nulling algorithms and calibration to support multiple beams
- Is costly – requiring *M* times LNAs/PAs and *M* times the PCB/antenna area

Hybrid BF vs Digital BF

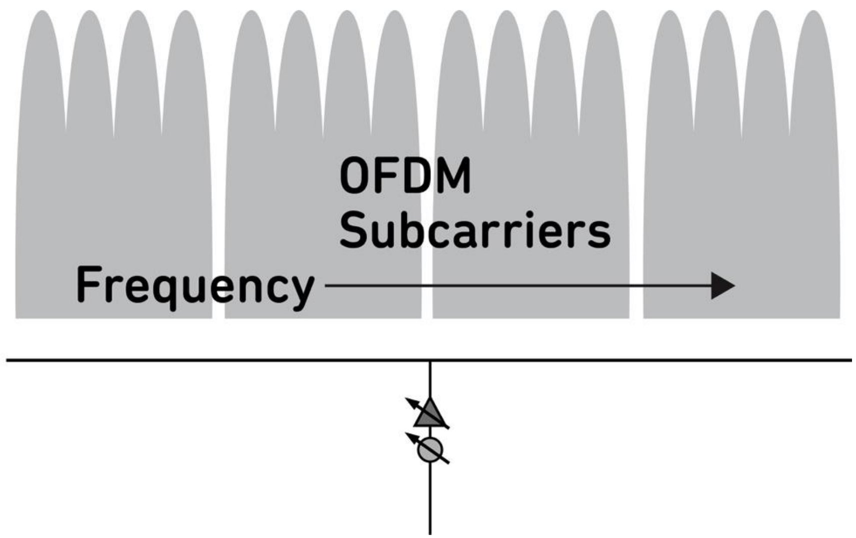
All-digital BF allows per-subcarrier/channel beamforming

Digital Beamformer



Per-Subcarrier/Channel Beamforming

Analog Beamformer



One-weight for entire bandwidth

- Analog beamforming can only form a single solution for entire carrier bandwidth
- Susceptible to frequency selective channels for NLOS conditions

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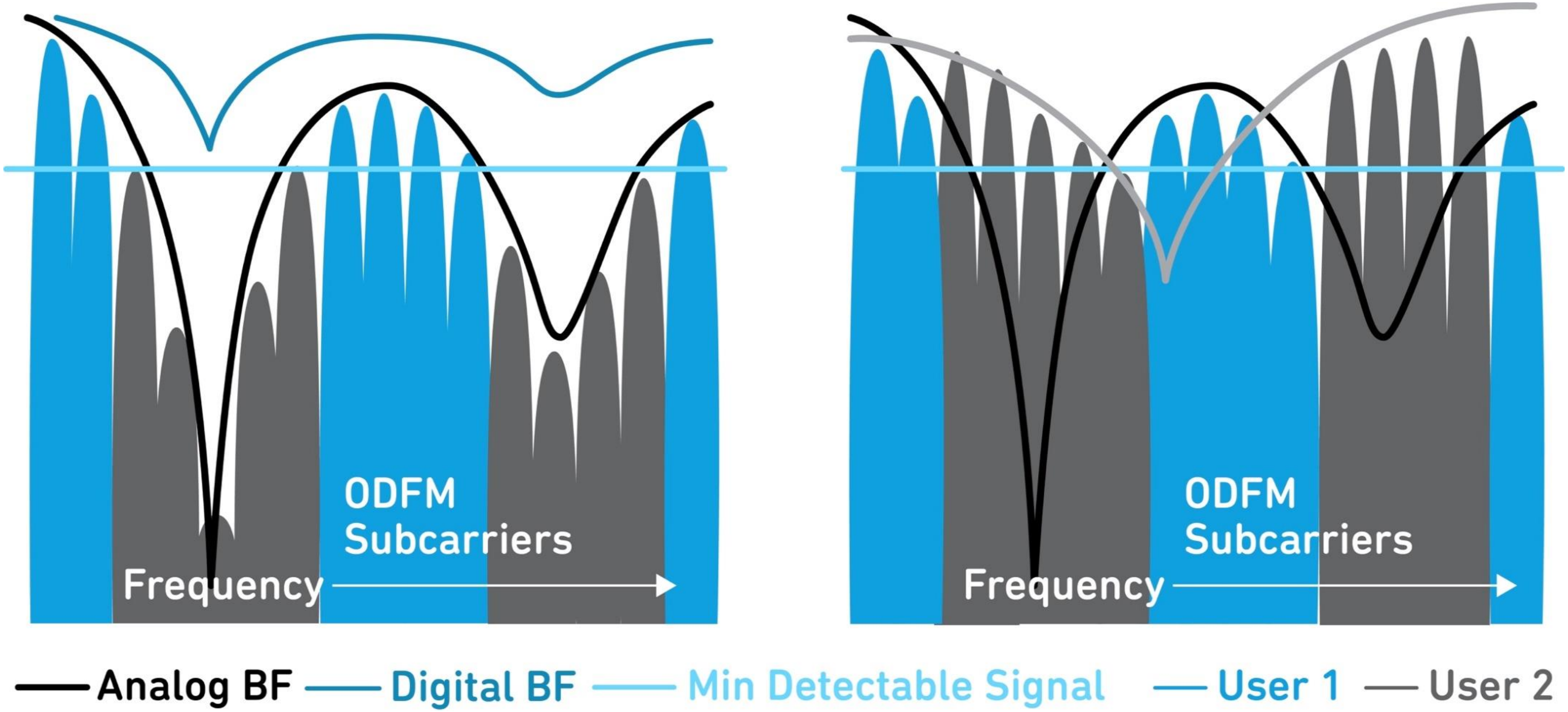
Hybrid BF vs Digital BF

All-digital BF has advantage for frequency selective channels

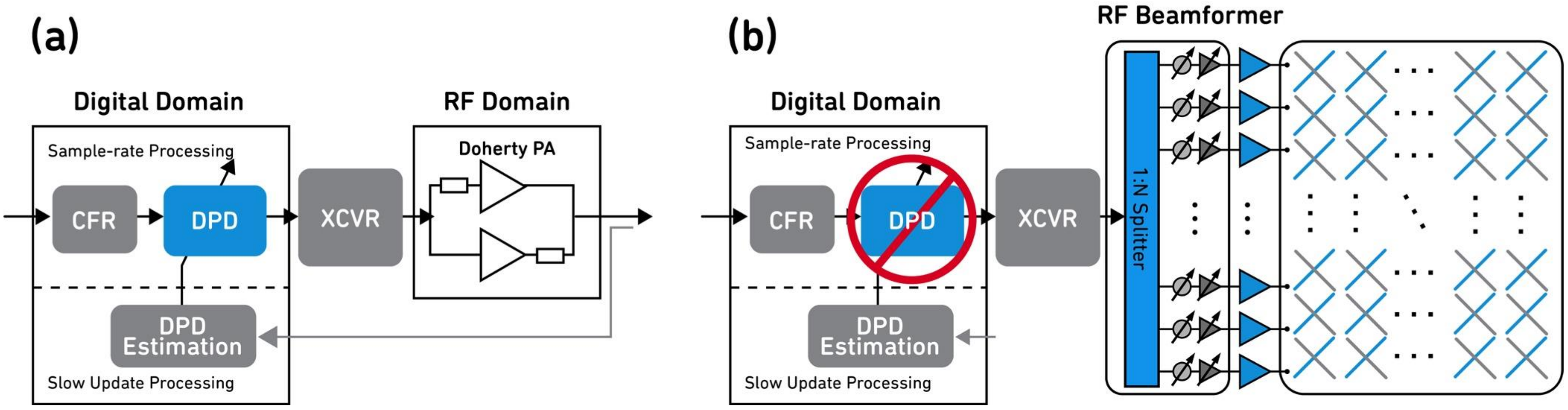


- Per-subcarrier/channel beamforming to equalize the channel, or
- Can form multiple beams simultaneously to different users – better channel use

Hybrid BF vs Digital BF

DPD+Doherty approach is not possible w/Hybrid BF

- **DPD and Doherty are essential for high-power high-efficiency – both for sub 6 GHz mass-MIMO and macro BTS**



Critical for Today's BTS | **Big Step Backwards**

- **DPD for 1:N hybrid beamforming is a challenging new research area**
- **Until it is solved we need to use linear PAs that typically have backed-off PAE in the single digits**

Hybrid BF: Semiconductor Technology

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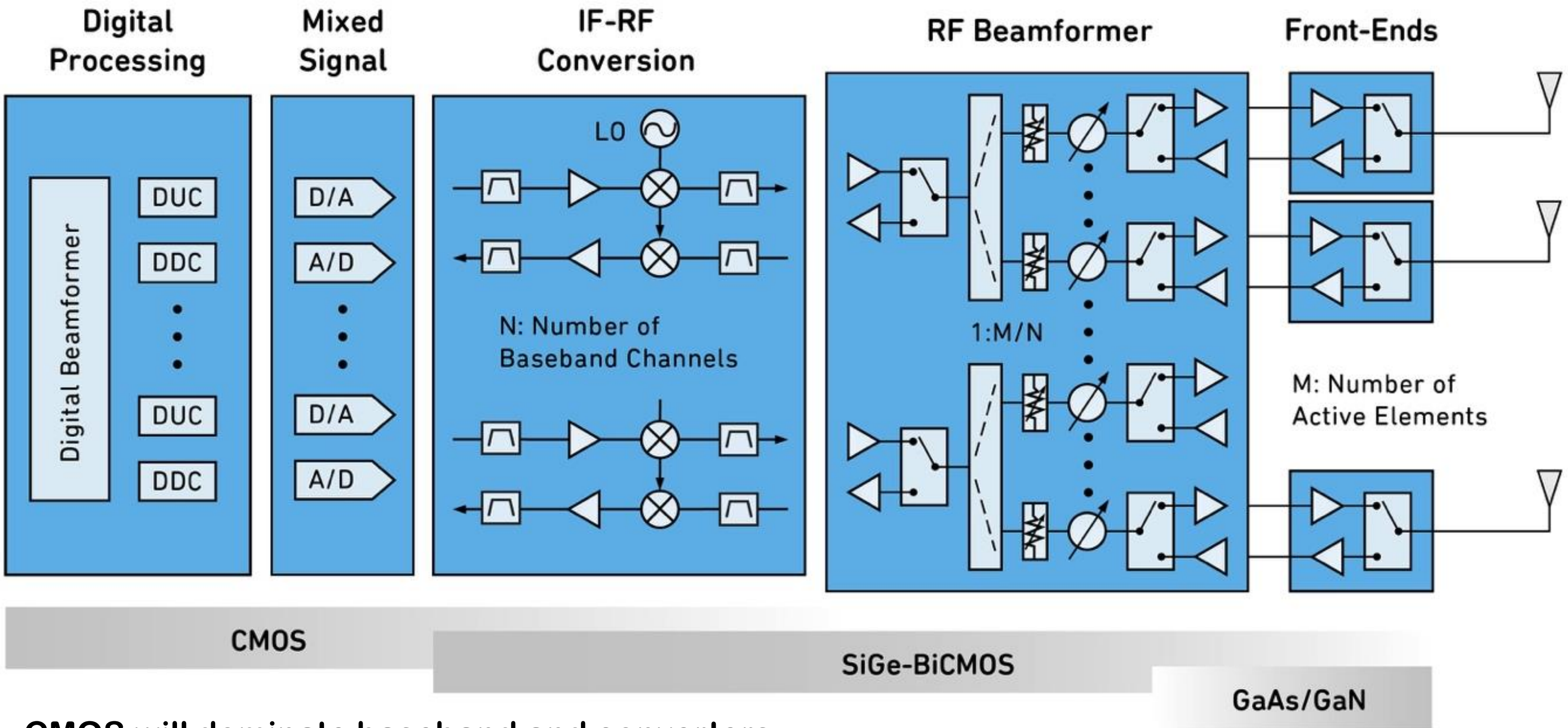

- CMOS will dominate baseband and converters
- SiGe BiCMOS seems a good choice for mixer and analog-BF
- But what about the front-end?
  - GaAs is a tried and true solution
  - GaN has many advantage for high power in tight spaces
  - But some are saying SiGe BiCMOS can do it all – is it really a good fit?

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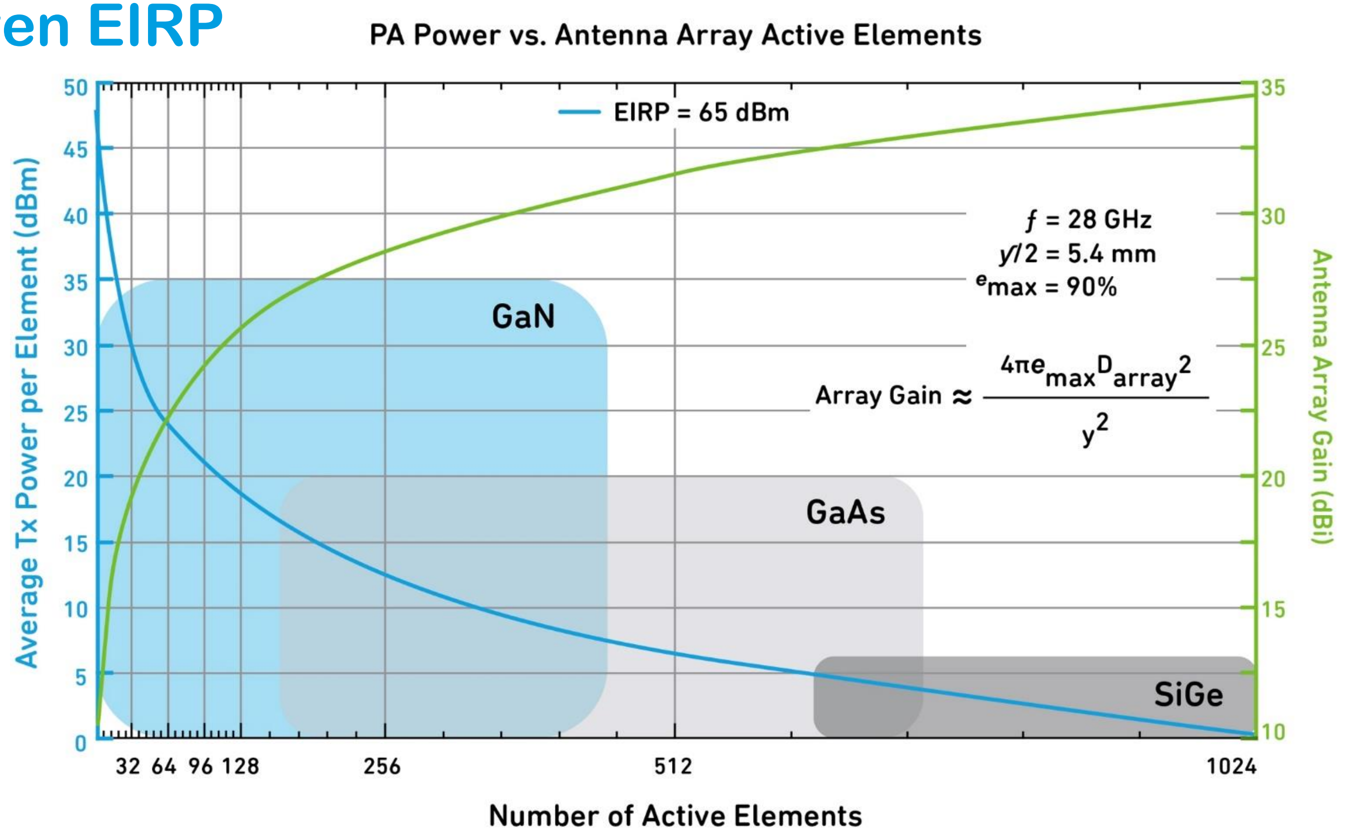
Semiconductor Technology vs Elements/Panel

PA power/channel reduces as number of elements increases for a given EIRP



- Beamforming circuitry becomes larger and more complex
- With enough elements SiGe/SOI is possible but is it optimal?

As Array Gets Large, Beams Get Narrow

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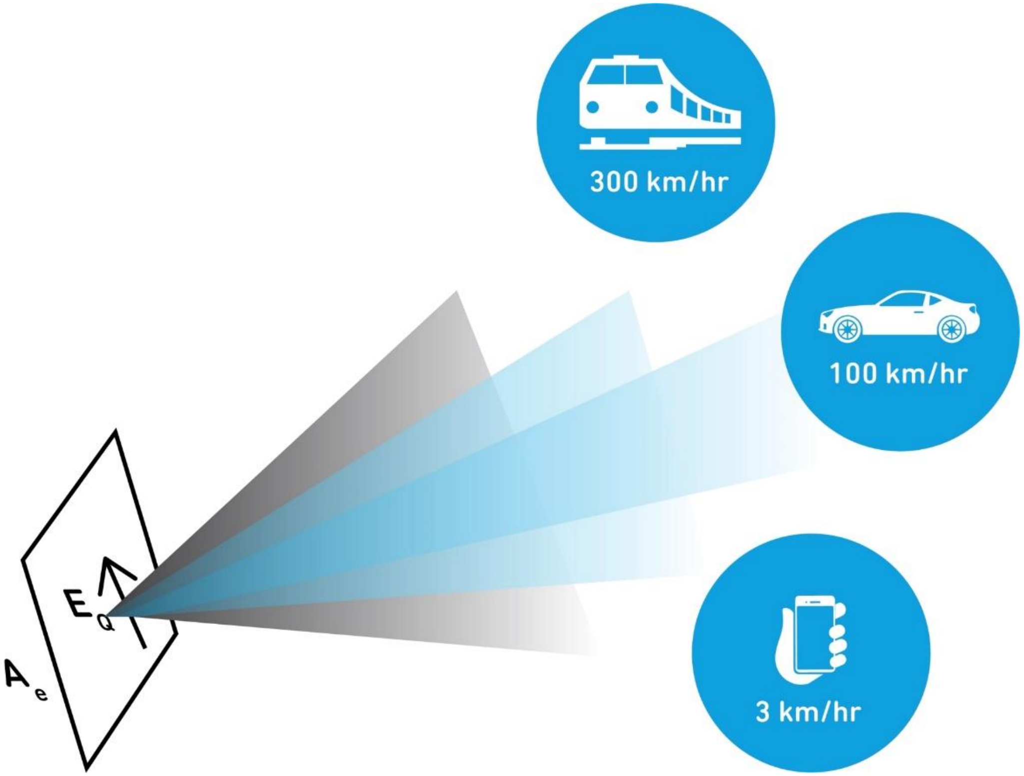


Half Power Beamwidth: 102°/N
Linear Array Gain: ~10log(N)+5dBi

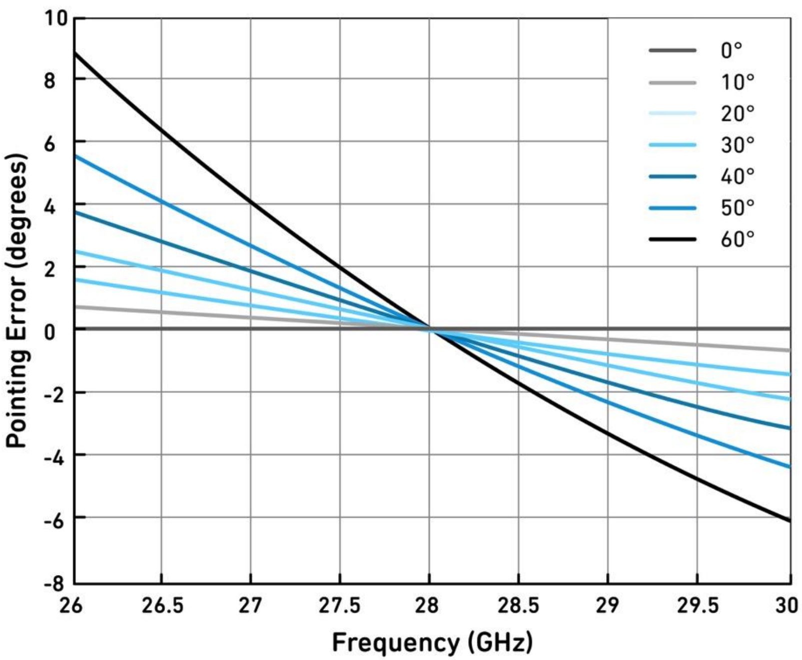
Array Size	AZ	EL	Gain (dBi)
4x4	25°	25°	17
8x8	12.75°	12.75°	23
16X16	6.5°	6.5°	29
32x32	3.25°	3.25°	35

- Narrow beamwidths make tracking mobile users challenging
- Also increases the precision and complexity of RF
- Expect some practical limits below ~10° for mobility

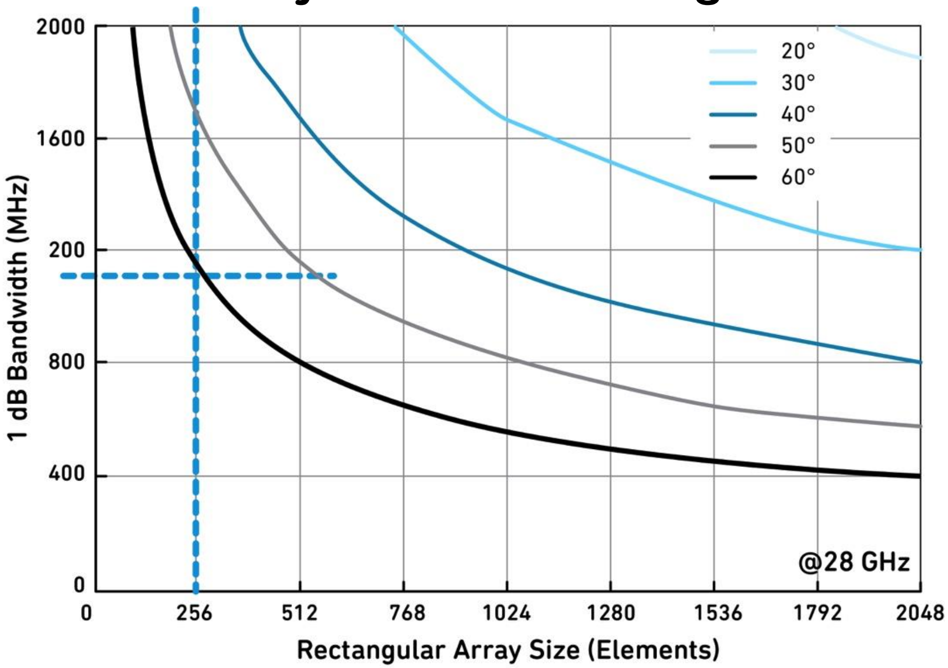
Beamwidth/Bandwidth Trades in Phased Array

Beam squint limits the bandwidth of the system

Pointing Error vs Frequency at Scan Angle



1 dB Beam Squint Bandwidth vs Array Size at Scan Angle



To support 5G bandwidths and high scan angles the subarray panel size will be limited to less than 256 elements

Array Size and Power Consumption

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DC power consumption and complexity trade-off

- DC power vs number of ant elements
- EIRP set to macro-cell levels: 60 dBm
- BTS RF power budget is constrained to 80 Watts

- N-element phased array EIRP in terms of RFE efficiency (PA efficiency, BEOL loss)

$$EIRP = NG_{el}\eta_{Ap}P_{TOT} = (NG_{el}\eta_{Ap})\left(\frac{P_{DC}}{\eta_{FE}}\right)$$

$$\Rightarrow \quad P_{DC} = \frac{EIRP/G_{el}}{\eta_{FE}N} + P_{overhead}$$

Number of Active Elements

RFFE Efficiency	2	4	8	16	32	64	128	256	512	1024
1%	17568.2	7874.1	4392.1	2196.0	1098.0	549.0	274.5	137.3	68.6	34.3
2%	8784.1	4392.1	2196.0	1098.0	549.0	274.5	137.3	68.6	34.3	17.2
3%	5856.1	2928.0	1464.0	732.0	366.0	183.0	91.5	45.8	22.9	11.4
4%	4392.1	2196.0	1098.0	549.0	274.5	137.7	68.6	34.3	17.2	8.6
6%	2928.0	1464.0	732.0	366.0	183.0	91.5	45.8	22.9	11.4	5.7
8%	2196.0	1098.0	549.0	274.5	137.3	68.6	34.3	17.2	8.6	4.3
10%	1756.8	878.4	439.2	219.6	109.8	54.9	27.5	13.7	6.9	3.4
12%	1464.0	732.0	366.0	183.0	91.5	45.8	22.9	11.4	5.7	2.9
14%	1254.9	627.2	313.7	156.9	78.4	39.2	19.6	9.8	4.9	
16%	1098.0	549.0	274.5	137.3		34.3	17.2	8.6	4.3	2.1
18%	976.0	488.0	244.0	122.0	61.0	30.5	15.3	7.6	3.8	1.9
20%	878.4	439.2	219.6	109.8	54.9	27.5	13.7	6.9	3.4	1.7
22%	798.6	399.3	199.6	99.8	49.9	25.0	12.5	6.2	3.1	1.6
24%	732.0	366.0	183.0	91.5	45.8	22.9	11.4	5.7	2.9	1.4
26%	675.7	337.9	168.9	84.5	42.2	21.1	10.6	5.3	2.6	1.3
28%	627.4	313.7	156.9	78.4	39.2	19.6	9.8	4.9	2.5	1.2
30%	585.6	292.8	146.4	73.2	36.6	18.3				
RF Avg Pwr/ Ant (dBm)	49.4	43.4	37.4	31.4	25.4	19.3	13.3	7.3	1.3	-4.7

GaN | GaAs | SiGe/SOI | CMOS

Typical total efficiency for SiGe phased array front-end is < 2%

Integrated SiGe phased array would require at least 256 elements at 2% efficiency

High power FEM

Within 80W power budget

Requires only 16 elements with high efficiency mmWave Doherty-PA

Assumptions:	
Antenna Efficiency	90%
Unit Ant Gain	5 dB
EIRP	60 dBm
DC Budget	80 W

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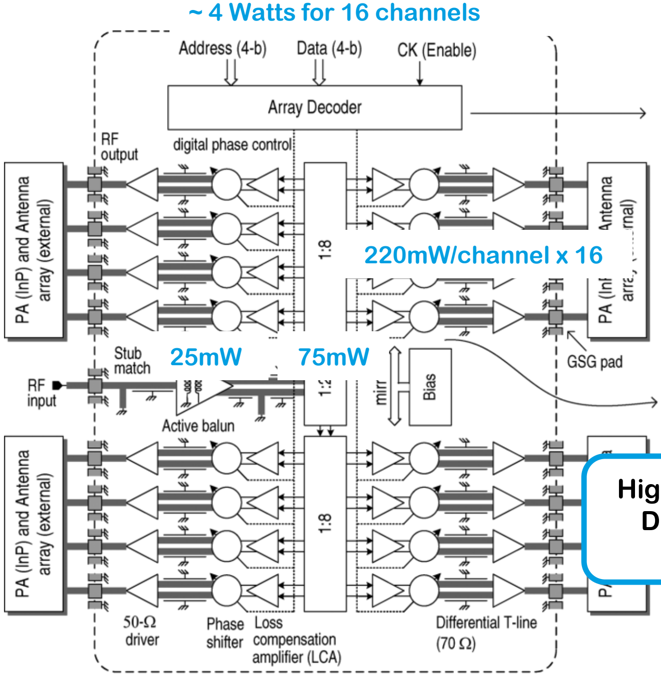
Don't Forget to Add Pdc of Beamformer

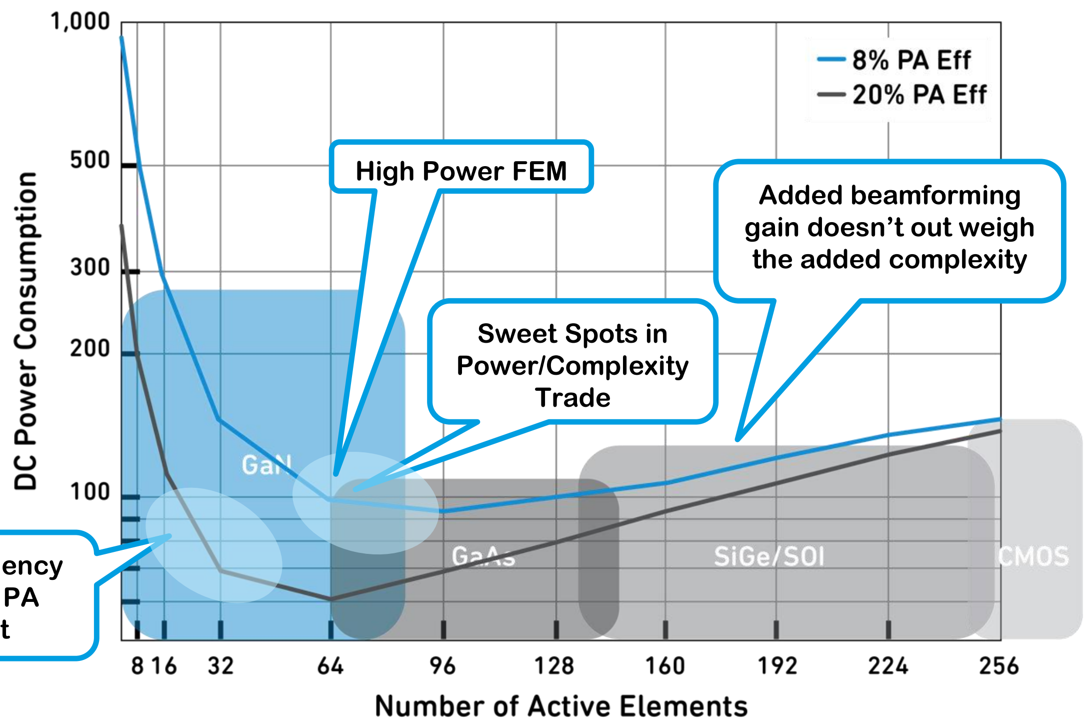
Further analysis on DC power consumption and complexity trade-offs

- SiGe beamformers typically consume greater than 200mW/channel
- Going to 128-256 element subarrays may allow all Si solution but not optimal for power consumption

Ref: A Millimeter-Wave 16-Element Phased Array Transmitter in SiGe BiCMOS - Rebeiz

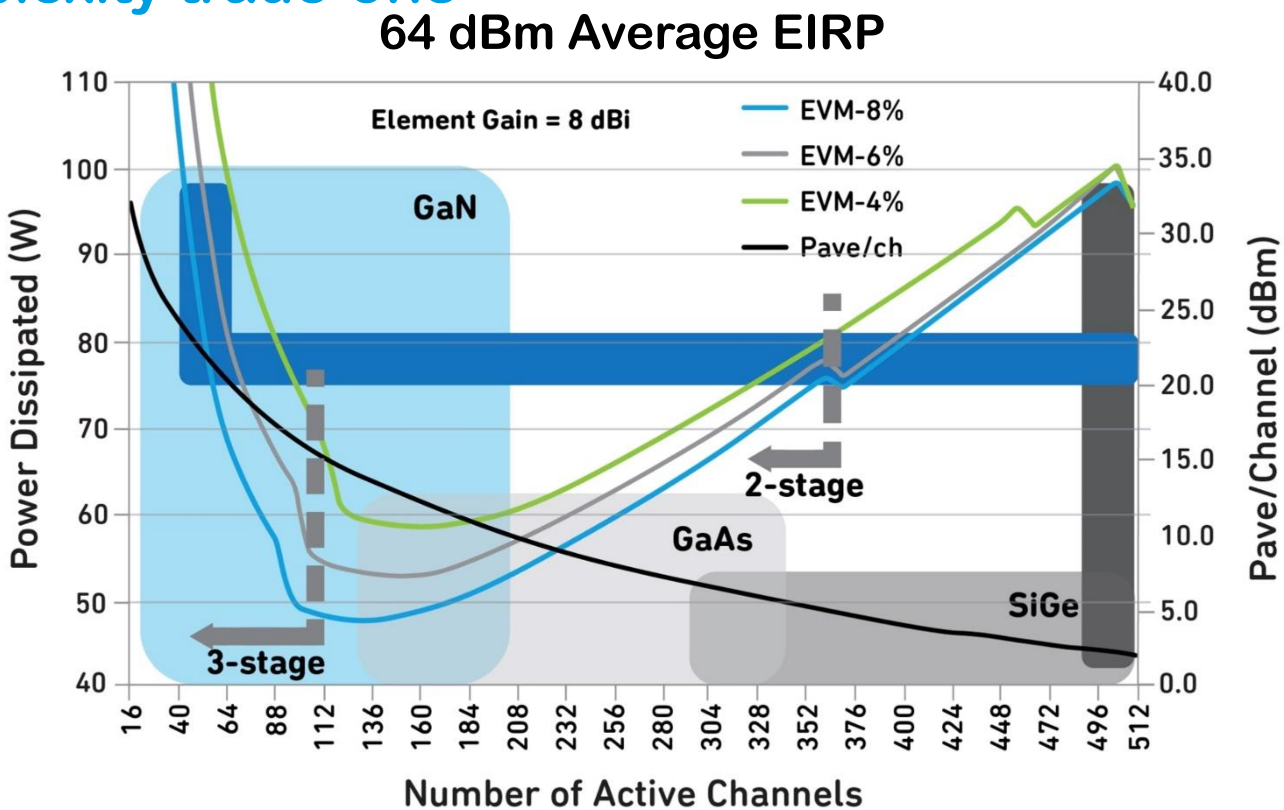


DC Power Consumption vs Number of Active Elements for EIRP=60 dBm



Does All SiGe Solution Scale to High EIRP?

Further analysis on DC power consumption and complexity trade-offs

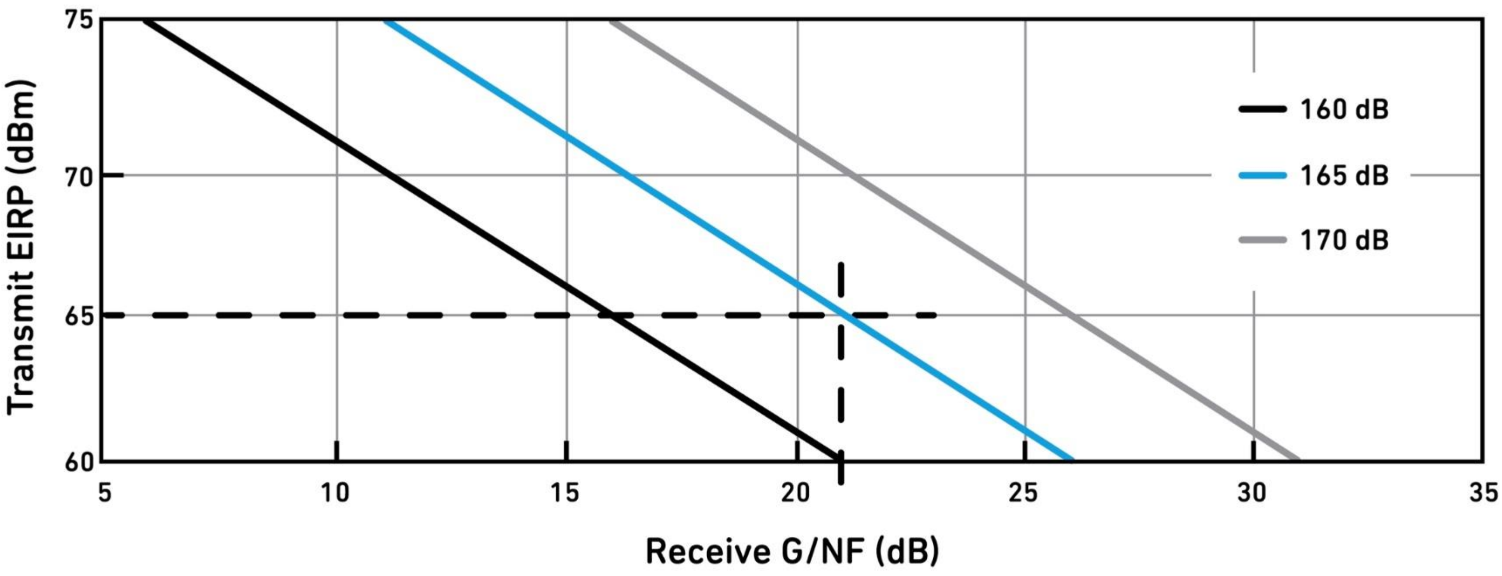


A combination of SiGe core-BF + high efficiency III-V FEM seems the best choice for lowest system complexity and more importantly – power dissipation

Closing the Link: Takes Two to Tango

Transmit EIRP vs receive G/NF vs pathloss budget

- Transmit EIRP and receive G/NF at target path-loss delivering 1 Gbps edge-of-coverage throughput



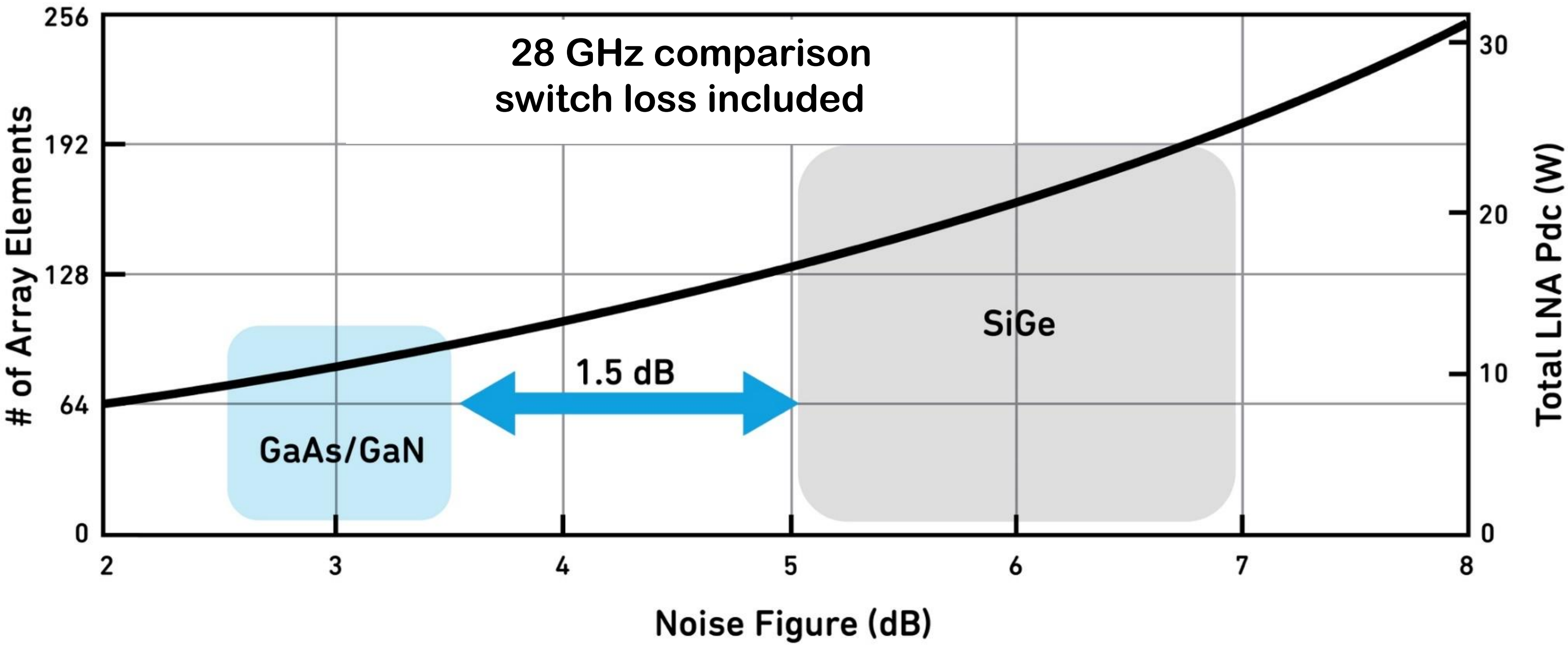
2 bps/Hz
SNR: 8 dB
BW: 500 MHz

- For example, 65 dBm BTS EIRP will be needed to sustain a 1 Gbps link at 165 dB of pathloss when the CPE receiver is ≥21 dBi G/NF

Noise Figure Matters

Minimum array size to achieve G/NF of 21 dB

- Array size is quite sensitive to noise figure



- Compound semiconductor technology provides ≥1.5 dB advantage
- Translating to a 30% savings in array size, power, and ultimately cost

QPF4005 39 GHz GaN15 FEM

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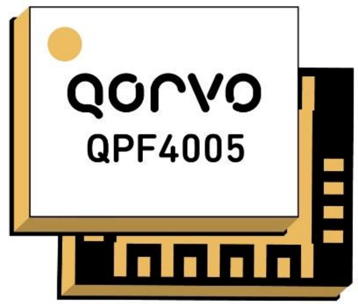
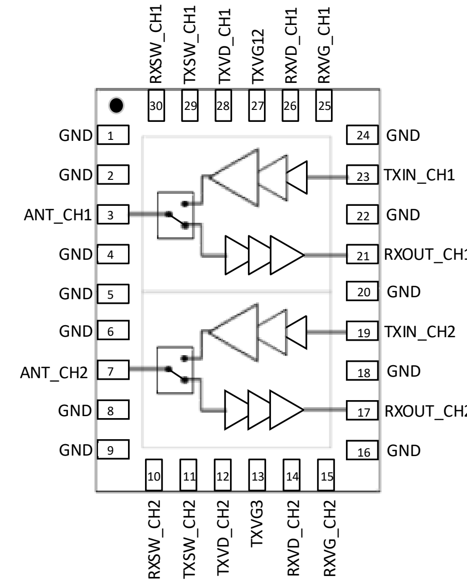
Product Features:

- Dual-channel GaN/SiC FEM
- Designed for 5G mmWave base stations and terminals
- Frequency range: 37 GHz to 40.5 GHz
- Receive path (LNA+SW):
  - Gain: 18dB
  - NF: <4.2dB
- Transmit path (PA+SW):
  - Gain: 24 dB (small-signal)
  - Psat: 2W/channel
  - PAE: 6-7% @ 24 dBm
- Compact 4.5 x 6 x 1.8 mm AC-EHS-L SMT

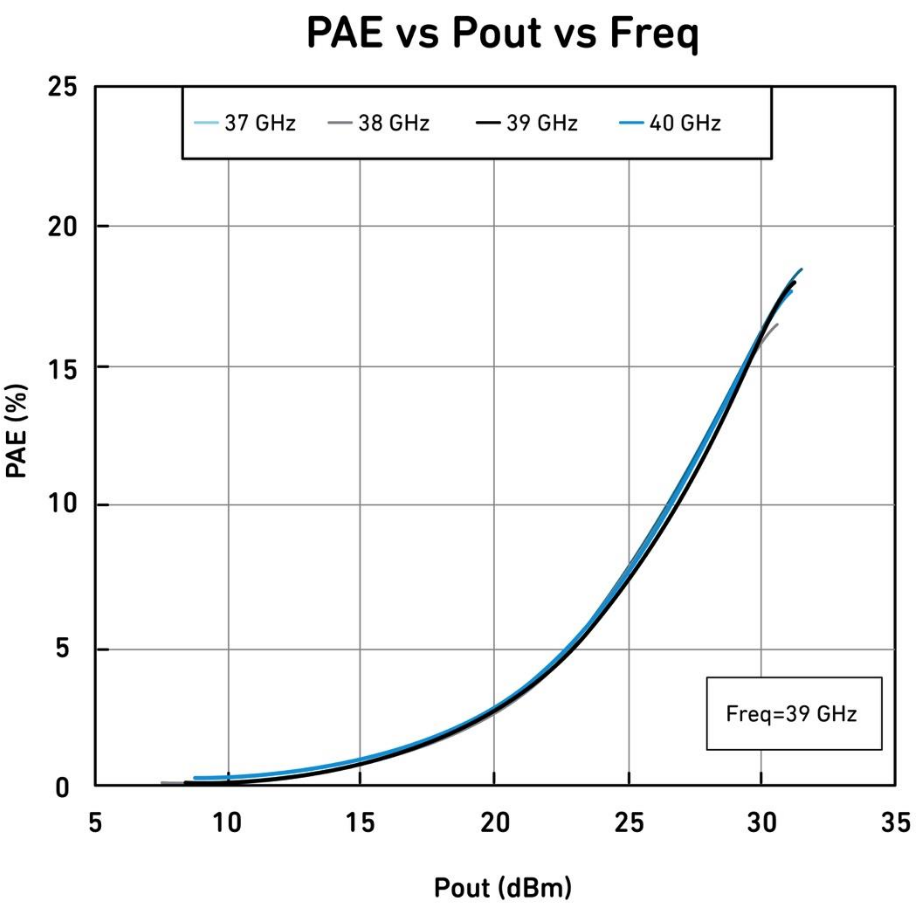


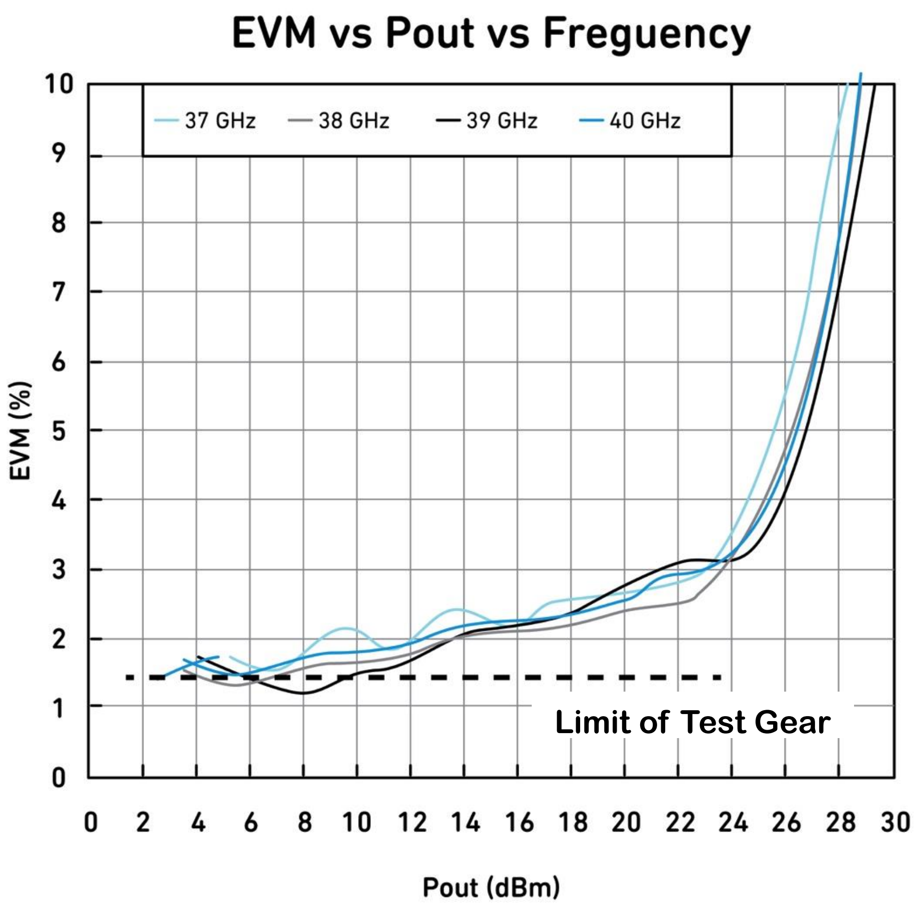


2700um x 1875um

Only FEM of its kind on market at 39 GHz
Twice the power of available GaAs PAs
First to have dual-channel package
Demonstrates GaN15 Process and AC-EHS Package Technology is ready up to 45 GHz

QPF4005: TX Measurements





https://www.qorvo.com/products/p/QPF4005

- Bias: Vd = 20V, Idq_Stage12 = 135mA, Idq_Final = 24 mA, Idq_Tot = 159mA
- Modulation: 400 MHz, CP-OFDM, QAM64, 60 kHz subcarriers

Linearity of GaN is very good

Integrated GaN FEMs for mm-Wave 5G

Family of FEMs

Part Number	Band (GHz)	Pave* (dBm)	Tx Gain (dB)	NF (dB)	Rx Gain (dB)	Dual-Channel Package	Availability
QPF4003/4	24.25-27.5	20/23	26	3.0	18	5.0 x 6.0 x 1.8 mm	2H2018**
QPF4001/2	26.5-29.5	20/23	25	3.5	17	5.0 x 6.0 x 1.8 mm	1Q2018
QPF4005	37.1-40.5	23	24	4.1	16	4.5 x 6.0 x 1.8 mm	Now

*Average power supporting QAM64 EVM levels

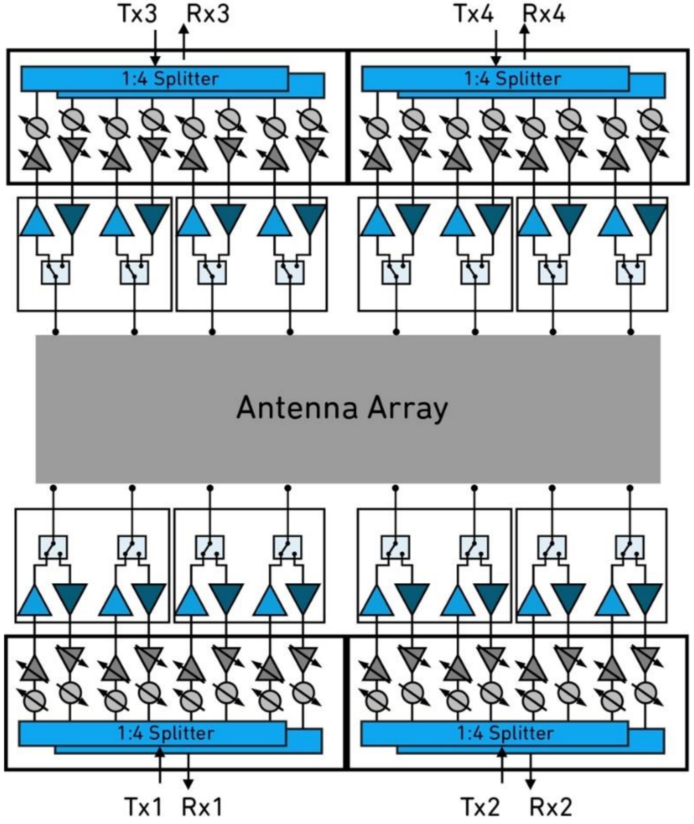
Product Features

- Integrated PA, LNA, & switch
- PAE @ 10dBBO of > 8% (includes switch loss)
- Very compact dual and single channel package
- Also allows multichip module w/ SiGe-BF + FEMs in single package

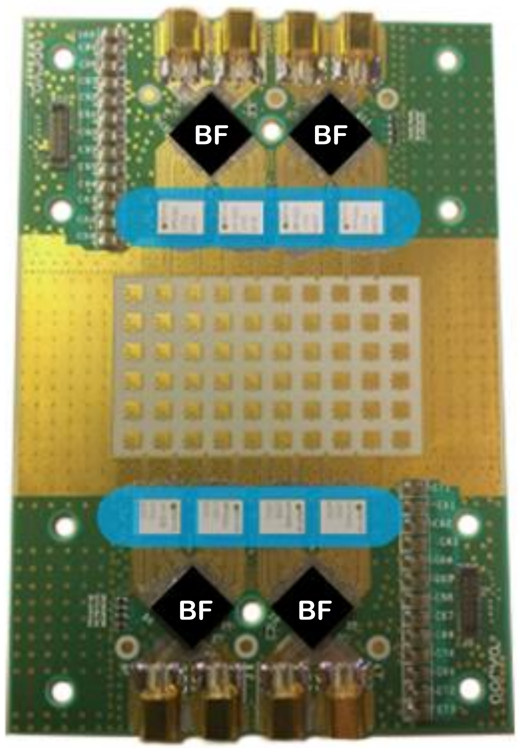
55dBm/Pol Average EIRP Planar-Array

Lattice spacing at 39 GHz – not a problem

Functional



Assembled Array



~2" x 3'

Features:

- 37-40.5 GHz
- 32 - dual polarized patch elements (4x8)
- 8-active columns x 4-passively combined elements
- Front-end
  - QPF4005 – dual chan PA+SW+LNA
  - 8-channels/pol, 16 total
  - 2W/channel (Psat)
  - 26.5 dBm Pave @6%EVM
  - 10% PAE @6%EVM
- SiGe analog beamformers
  - 4:1 TRx phase+amplitude
  - 8-channels/pol, 16 total
- System Pdc ~ 38W/pol
- AZ only beamforming

All SiGe vs GaN FEM Complexity and Cost Comparison at 65 dBm Average EIRP

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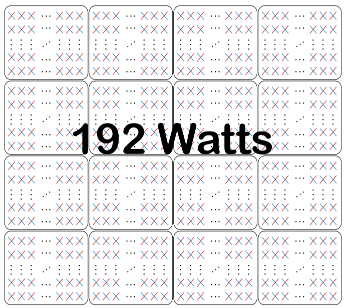
Today's all SiGe approach



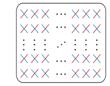
16x Less Die Area
10x Less Board Area
40% Less Power
80% Less Cost
Same EIRP

Vs

All SiGe-BF approach:

- Requires 16 64-element panels
- 1024 channels to achieve 65 dBm EIRP (single pol)
- Total power consumption: 192 Watts
- Die area:
  - 256 core-BF RFIC chips @ 4 x 4 mm die size, 16 sq-mm area
  - Total die area: 4096 sq-m
- Cost of 130nm SiGe: $Y

Qorvo Solutions: Today's SiGe BF+GaN FEM



- Only 1 panel needed
- 24-active columns x 4 passive elem
- Total power consumption: 113 W
- GaN FEM: 26.5 dBm pave, 10% PAE
- Die area:
  - 1.875 x 2.7mm, 5.1 sq-mm area
  - 8 core-BF RFIC chips: 128 sq-mm
  - 24 GaN FEM channels: 122 sq-mm
  - Total die area: 250 sq-mm
- Cost of 150nm 6" GaN: 5*$Y

Total System Cost Comparison:

- All SiGe: $(4096*Y)
- SiGe+GaN: 128*Y + 122*5*Y = $(738*Y)
- 80% cost reduction w/ SiGe+GaN solution

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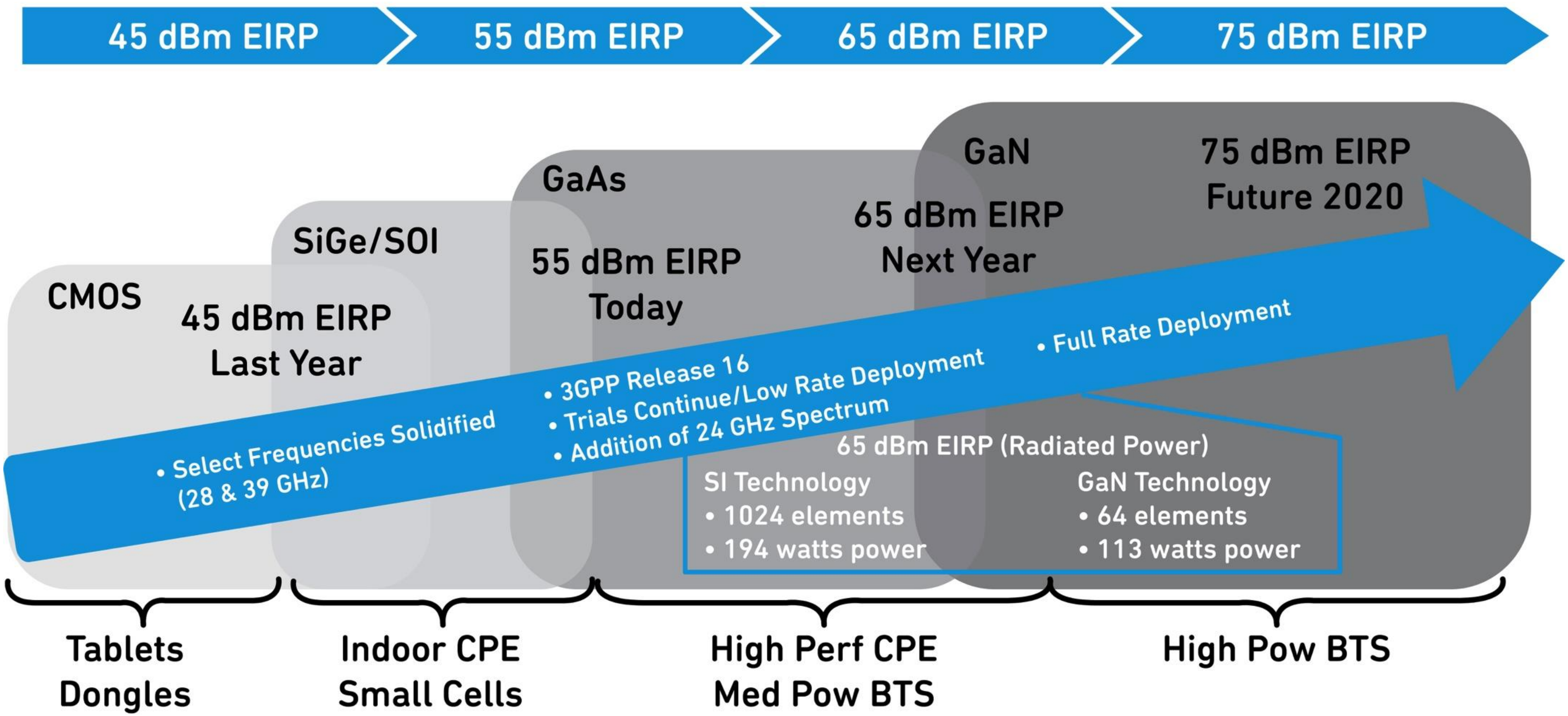
Target PA Requirements

Design target depends on architecture

Architecture	Number of Active Chains	PA Requirements	Implementation	Technologies
Low-Power PA Hybrid Beamform Array	256 and higher	Pave = 6-9 dBm P1dB = 14-17 dBm	Integrated beamforming RFIC, integrated FEMs (single MMIC)	SiGe, SIO or CMOS
High-Power PA Hybrid Beamform Array	32 to 128	Pave = 17-24 dBm P1dB = 25-32 dBm	Beamformer RFIC and internal/external FEMs (MCM)	Beamformer: SiGe or CMOS FEM (PA/LNA): GaAs or GaN
All-Digital Mass-MIMO	8 to 32	Pave = 27-33 dBm P1dB = 35-41 dBm Eff>20% Some DPD rqrd	Doherty PA and Switch/LNA modules No BF RFIC rqrd	PA: GaN LNA: GaAs or GaN

Semiconductor Technology

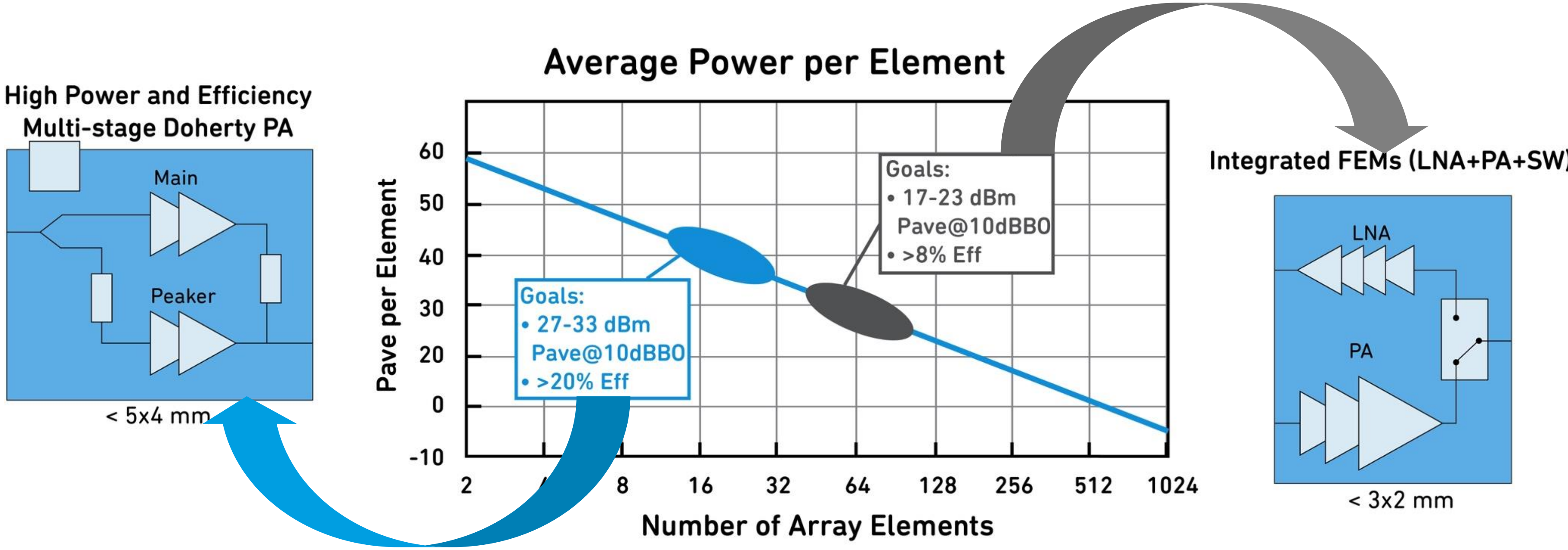
As EIRP increases the choice of front-end technology changes



Compound semiconductors will be critical to achieving high EIRP with optimized power dissipation and cost

PA Requirements

RF power target and PA design – depends on architecture



- **Architecture 1: high power, high efficiency with medium sized array**
  - PA powers above 27 dBm pave with > 25% efficiency needed
  - Expect all digital beamforming approach or simplified hybrid beamforming architecture
  - Minimizes number of RF chains allows superior digital beamforming
- **Architecture 2: low power highly integrated with large antenna arrays**
  - Lower PA powers required but compact size is very critical
  - Initially need to integrate PA, LNA, and SW and multichannel configurations, eventually will need hybrid packaging and integrated BF driver

Outline

- Introduction and scope
- The fixed wireless access use case
- Base station architectural trades
- All-digital beamforming architecture
- Hybrid beamforming architecture
- **Summary**

Summary

- Fixed wireless access requires high EIRP to close the link
- Two main architectures – hybrid and all-digital
- As the number of elements go up – PA semiconductor technology changes
- Currently all silicon front-end solutions are possible but not necessarily optimal
- Hybrid beamforming does not allow traditional DPD which in-turn means low-efficiency linear PA topologies
- A high-power high-efficiency PA (>20%) will enable the all-digital architecture, which allows a straight forward extension of sub 6 GHz BTS architectures to work at mmWave
- Integrating SiGe-BF w/III-V semiconductors is a good trade if you need high EIRP
- Cost and power trades can flip at the system level
  - Silicon is not always the lowest cost if you need a ton of it

Thank you