Multi fractal
SEMICONDUCTORS

Unlocking the mmWave spectrum and enabling the 4th IR – 5G - from small cells to massive MIMO and the IoT

6th May 2019, IEEE 5G Summit, Pretoria, South Africa

AGENDA

Let's begin!

IEEE

IEEE ComSoc™
IEEE Communications Society

IEEE Future NETWORKS™
Enabling 5G and Beyond

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Faculty of Engineering, Built Environment and Information Technology
Fakulteit Ingenieurswese, Bou-omgewing en Inligtingtegnologie / Lefapha la Boetšenere, Tikologo ya Kago le Theknolotši ya Tshedimošo

Welcome
Glad to be here!

Introduction
What is 5G really? New apps only?
What are the key enabling techs?

Market opportunity
What is the problem? Our niche.

Our value proposition
How we will make E-band a *coverage* spectrum.

Business strategy
What we've done and where we're going.

Q&A
Want to know more?

INTRODUCTION

What is 5G really? New apps only? What are the key enabling techs?

INTRODUCTION

Evolution of 5G

1990
Mobility
Roaming
9.6 Kb/s

2G

2003
Multi-media
2 Mb/s

3G

2010
Architecture
Efficiency
300 Mb/s – 1 Gb/s (LTE-A)

4G

5G

1000x
Mobile data volumes

10x – 100x
Connected devices

5x
Lower latency
< 1 ms

10x – 100x
End-user data rates
> 10 Gb/s

10x
Battery life for low power devices

Source: METIS

INTRODUCTION

Network as a service – SDN/NFV

Network Slicing

10 Gb/s

eMBB

Enhanced Mobile Broadband

3D video, VR, UHD

Work & play in the cloud

Augmented reality

Service-driven architecture

- Multiple services, standards & site types
- Multi-connectivity technologies (LTE, WiFi, Fibre)
- On-demand deployment (re-configurability)
- Flexible and fast orchestration of eMBB, uRLLC, mMTC

Smart buildings

Smart-cities

Industry automation

Mission critical apps

Self driving cars

1 million / km^2

mMTC

Massive Machine Type Communications

< 1ms

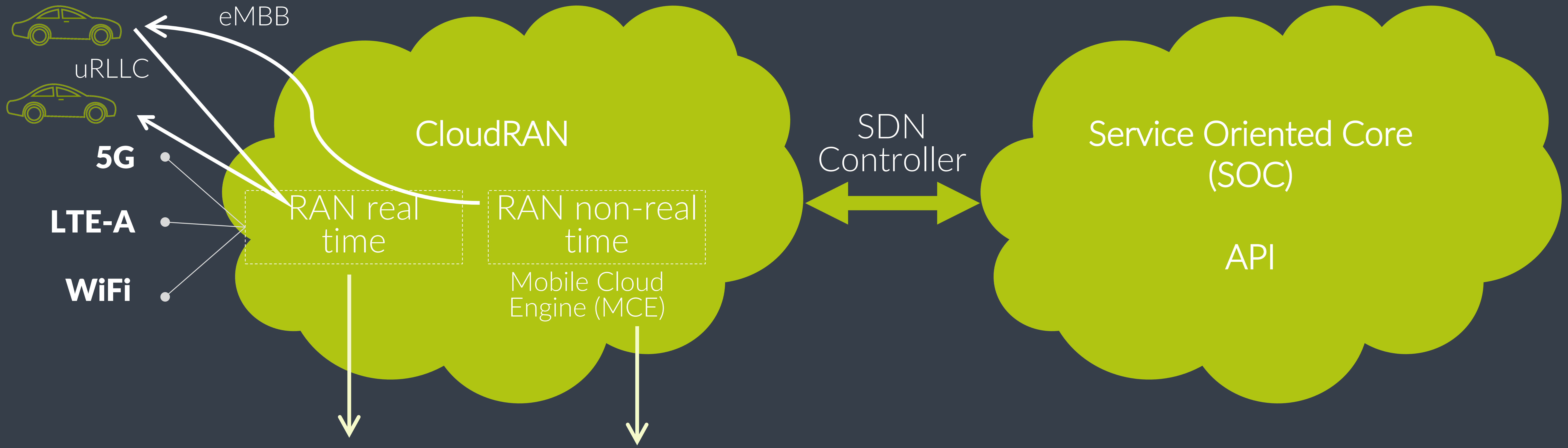
uRLLC

Ultra-reliable and Low-latency Communications

Source: Nokia

INTRODUCTION

Network as a service – SDN/NFV



- Access network scheduling
- Link adaption
- Power control
- Interference coordination
- Modulation
- Coding
- Beam-forming/steering
- Cognitive radio

- Inter-cell handover
- Cell selection
- UP encryption
- Multiple connection convergence

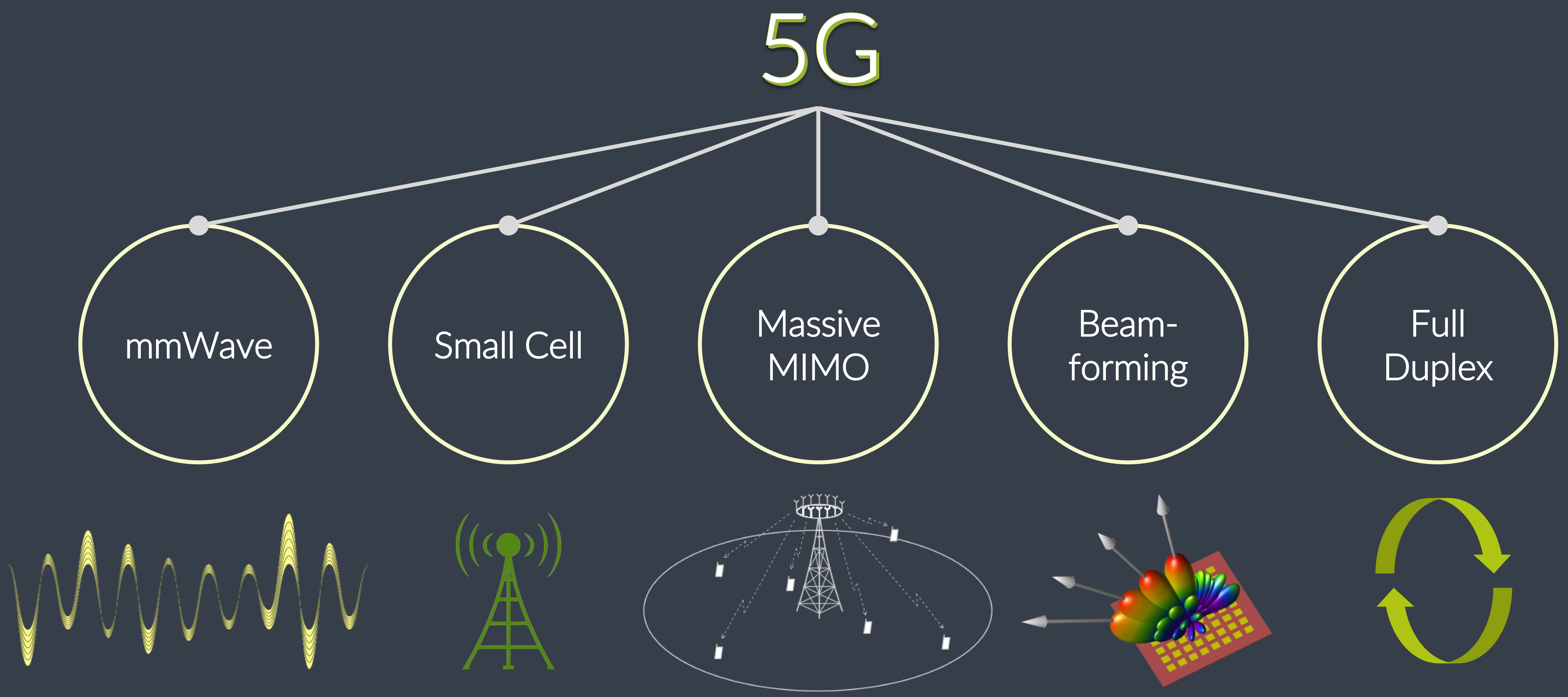
On-site dedicated hardware (close proximity)

Universal processing OK

Source: Huawei

INTRODUCTION

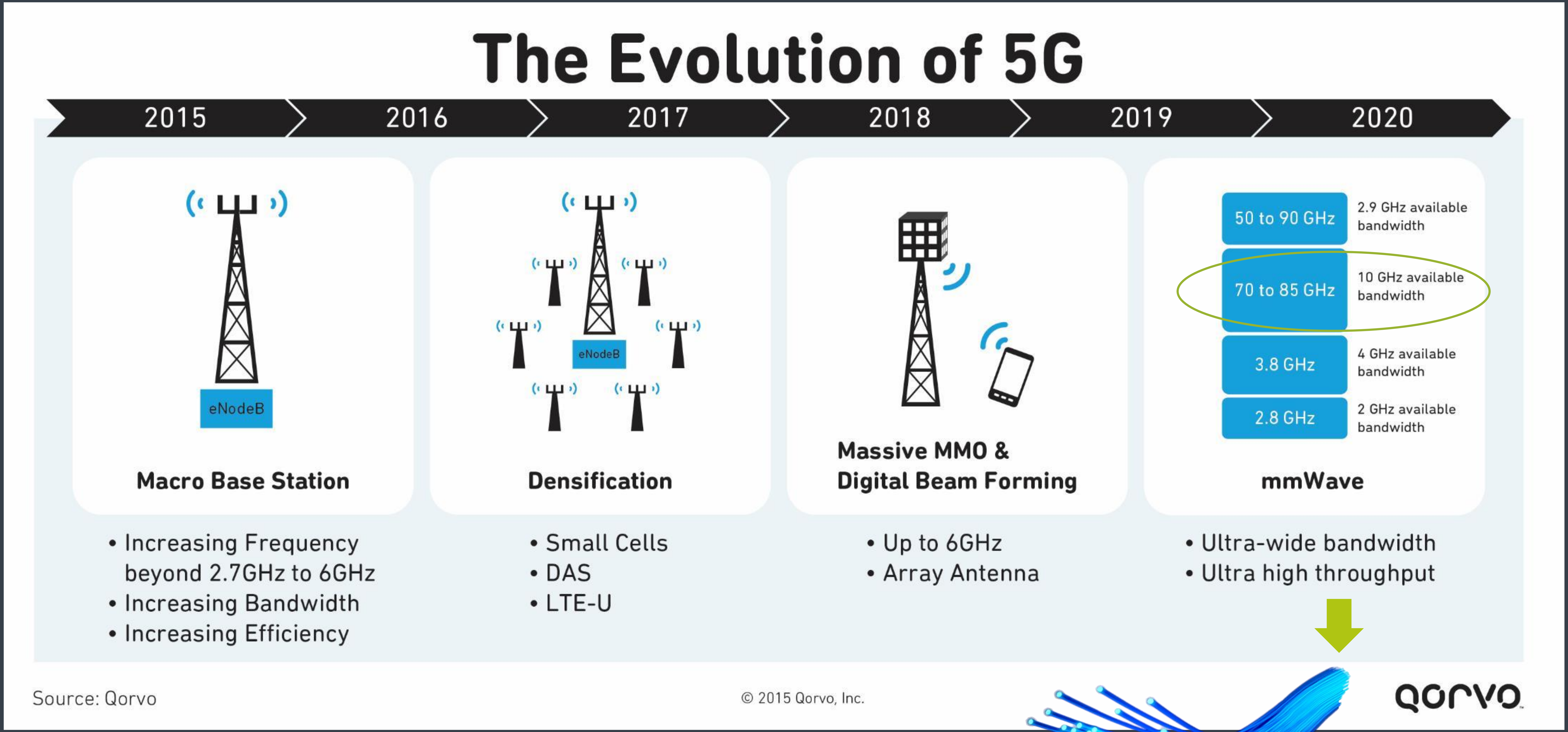
Key enabling 5G technologies

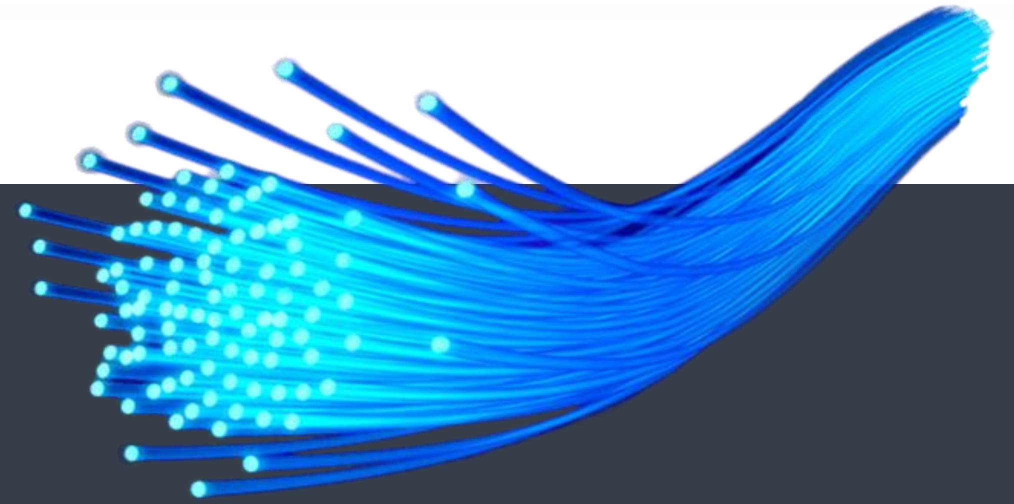


MARKET OPPORTUNITY

What is the problem? Our niche.

CHANGING LANDSCAPE

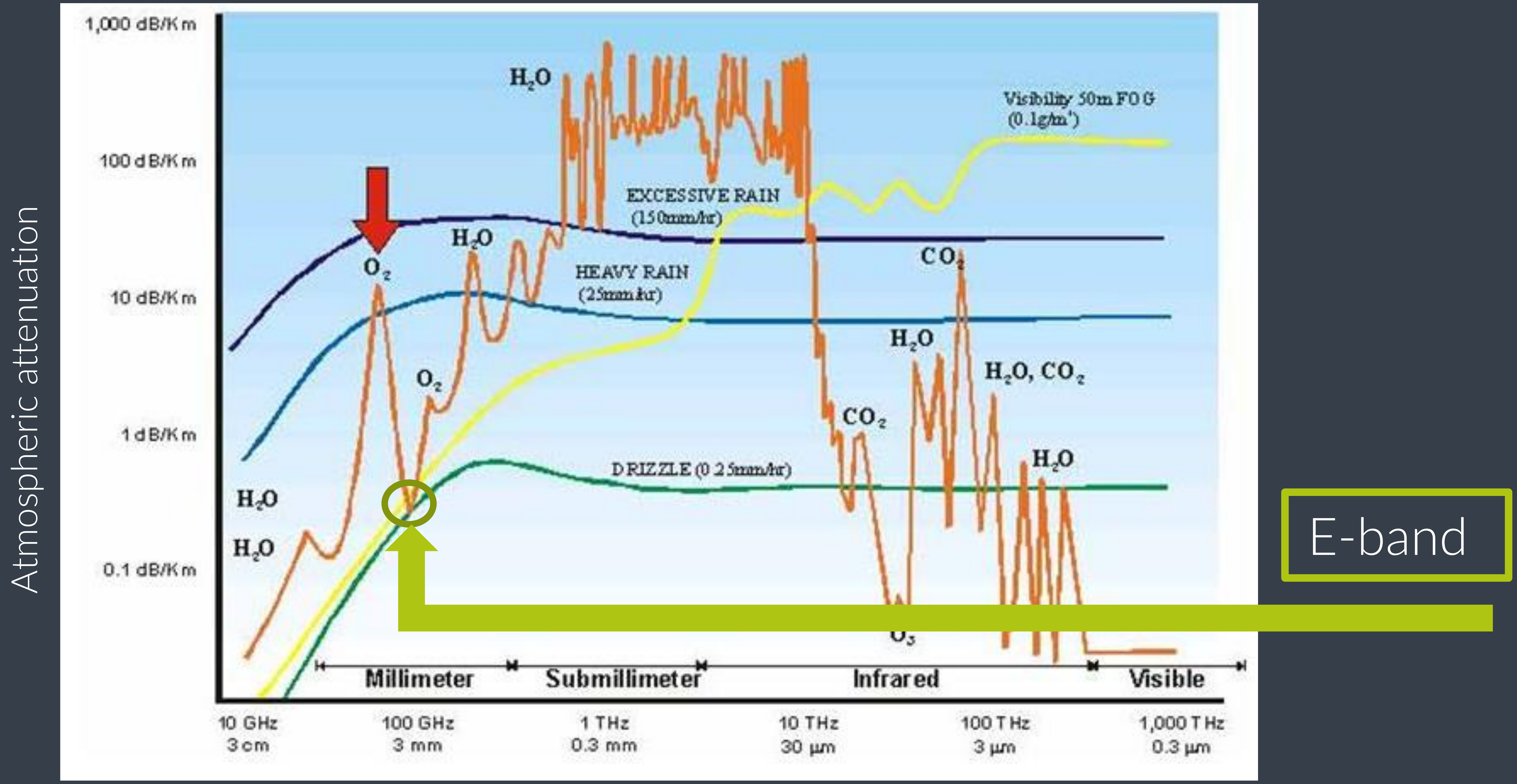




Fibre in the air!

E-BAND - THE NEXT FRONTIER (70-120 GHZ)

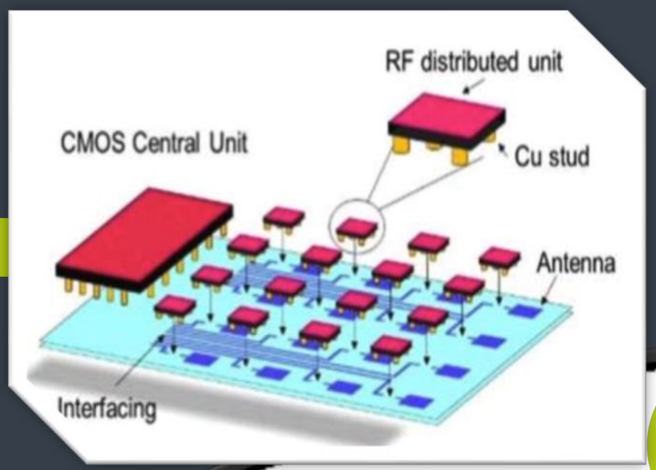
Why focus on E-band?

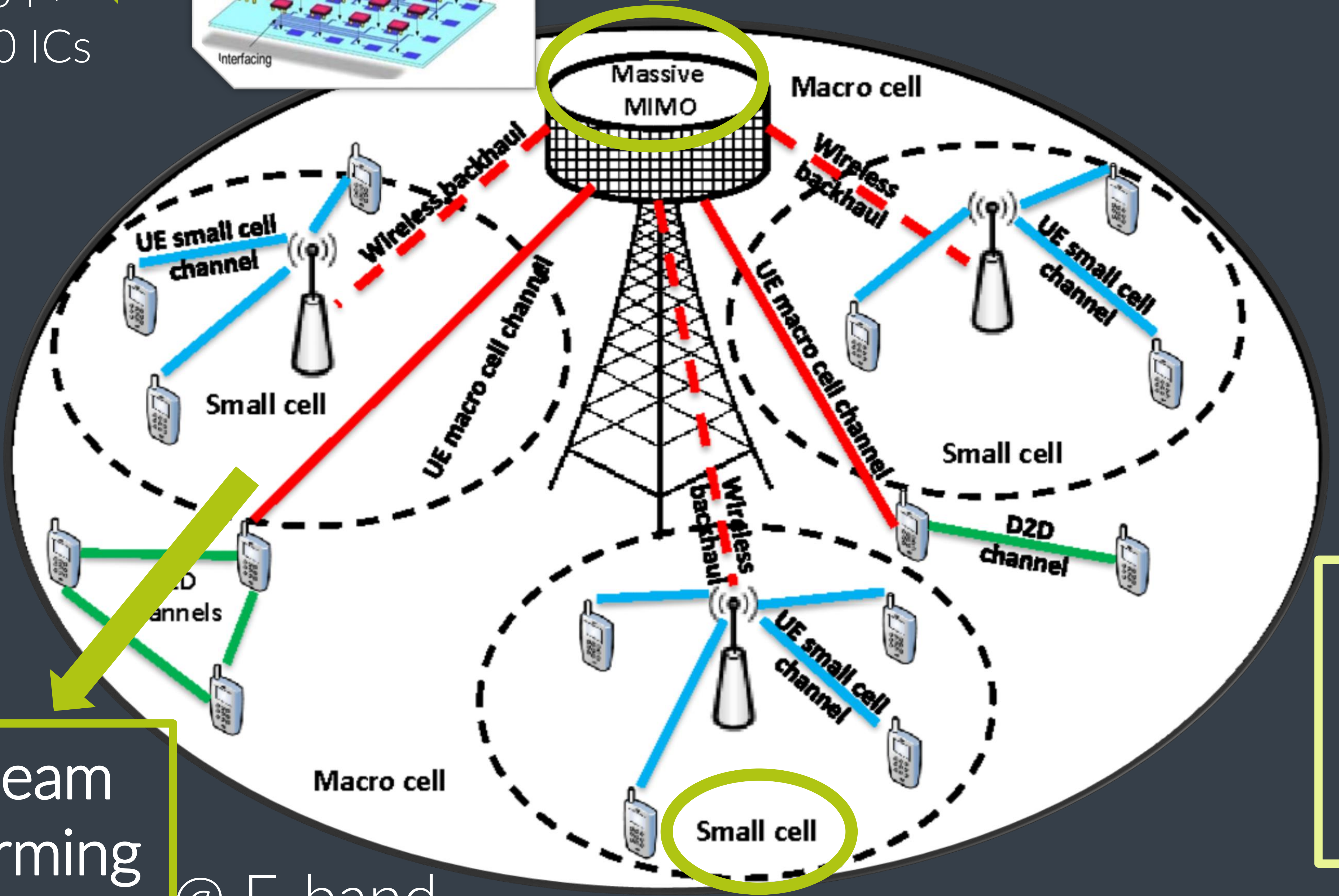


Gold mine! This opportunity will never appear in the radio spectrum ever again! Ever.

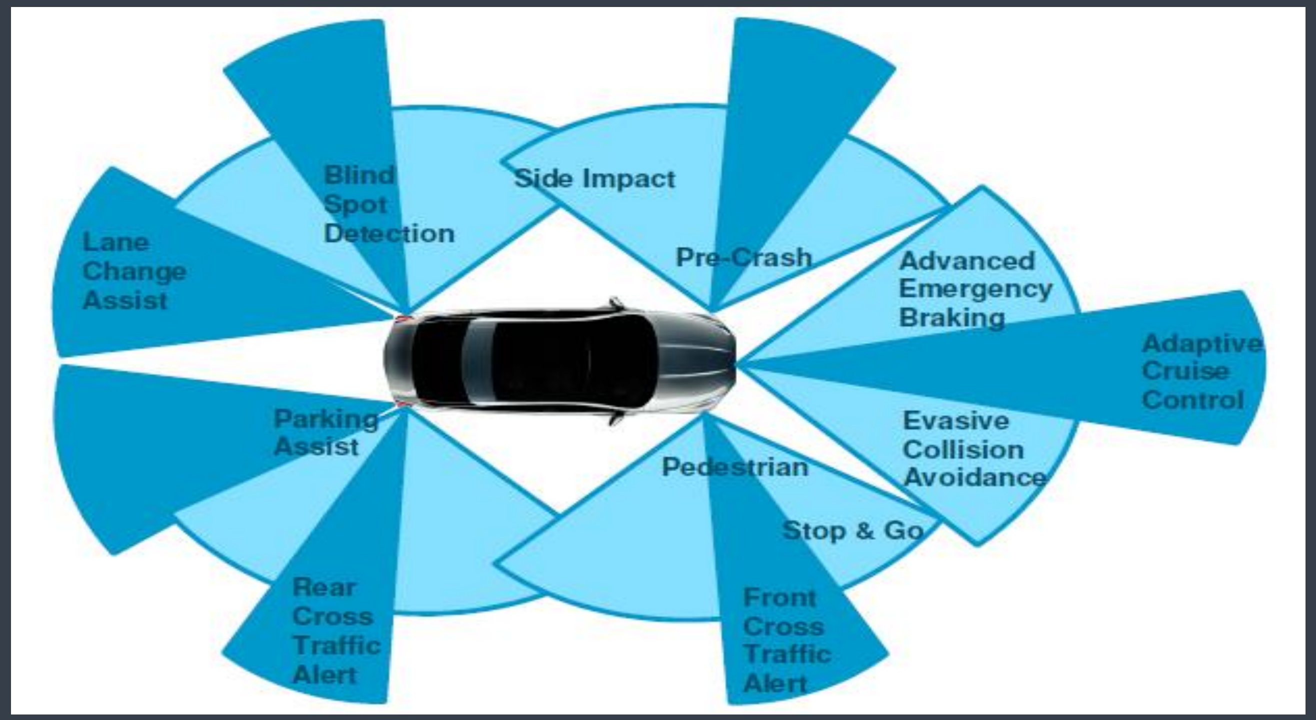
APPLICATIONS AND OUTLOOK

64x64 > 4000 ICs





MMIMO



Automotive RADAR

1. 5G Backhaul
2. 5G Fronthaul
3. Fixed wireless access
4. 5G Mobile access
5. Sat to surface
6. Automotive radar

We believe the world will be blanketed by E-band by 2025

Beam forming

@ E-band

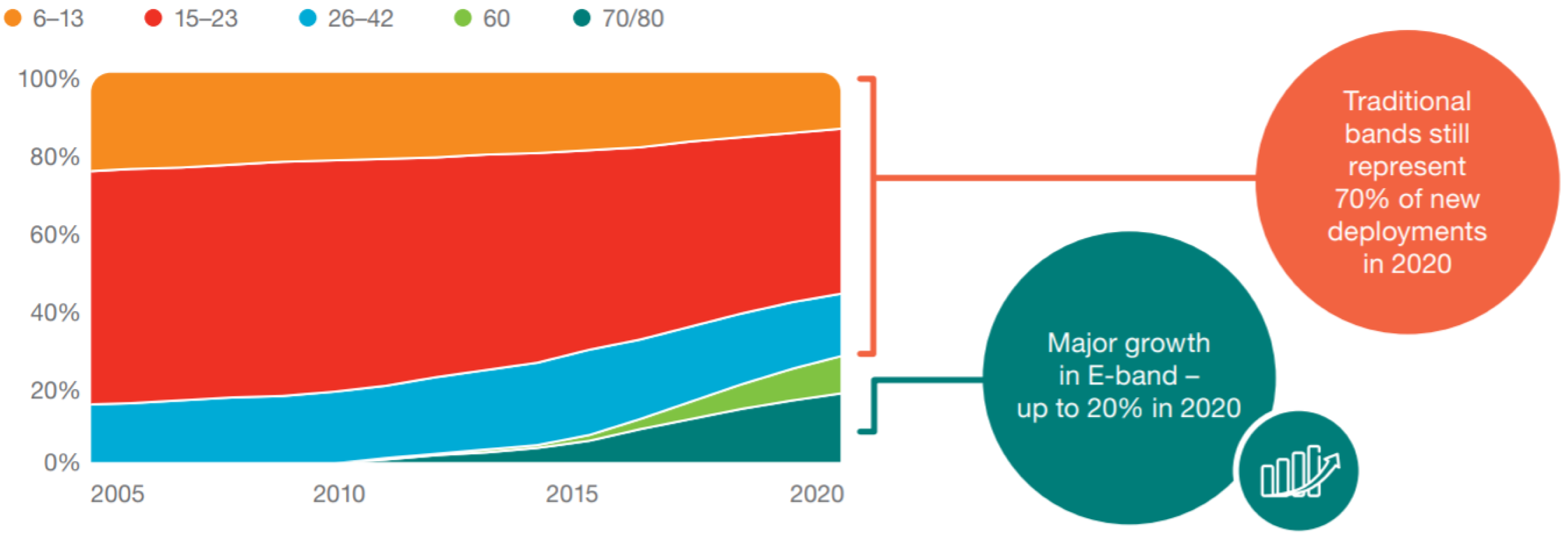
Gaps in market:

- No E-band filters on-chip
- DSP – big data problem

Small Cells

MAJOR INDUSTRY PLAYERS THINK SO TOO

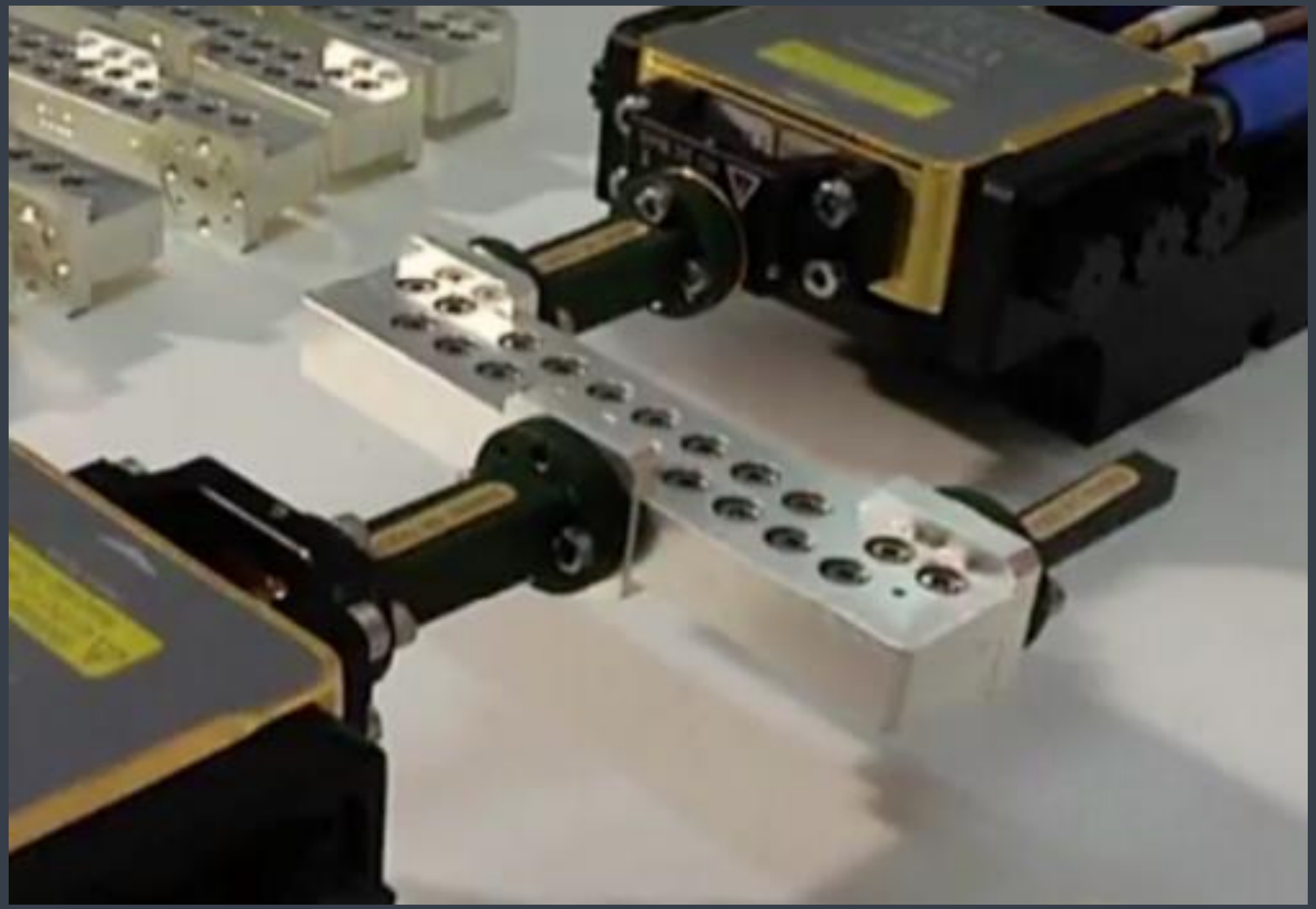
Figure 10: New deployment share per frequency range [GHz]

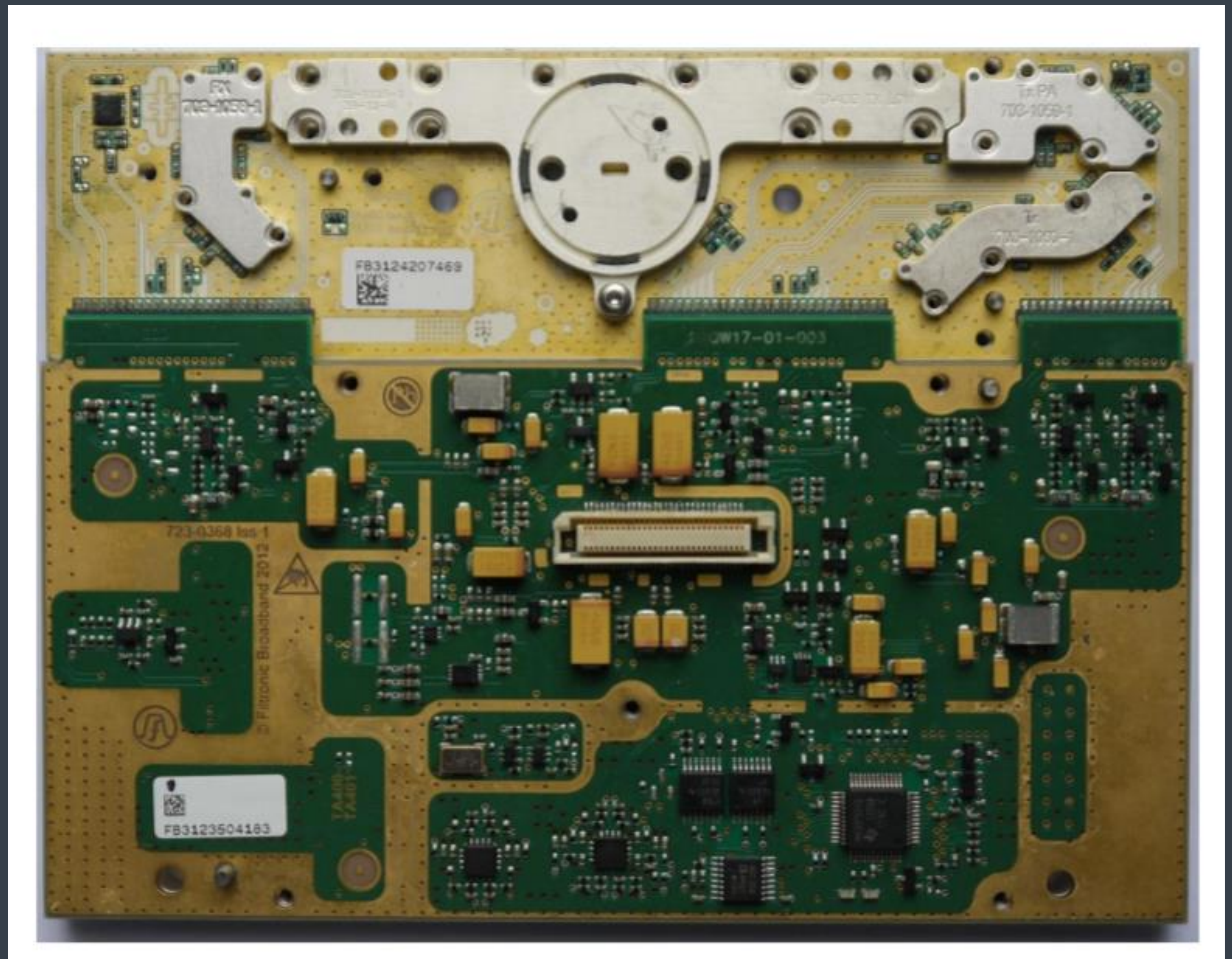


Source: Ericsson (2015)

8 ERICSSON MICROWAVE TOWARDS 2020

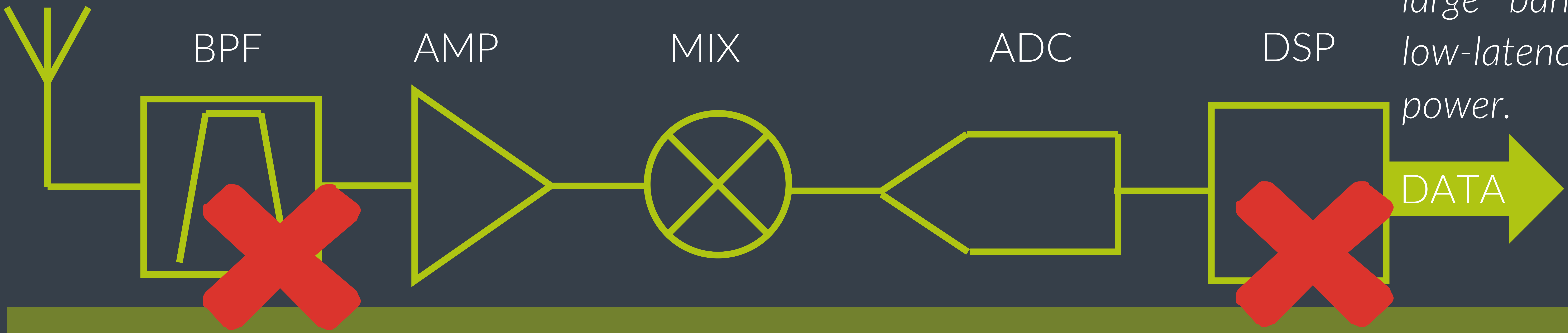
SO WHAT IS THE PROBLEM? BULKY FRONT ENDS

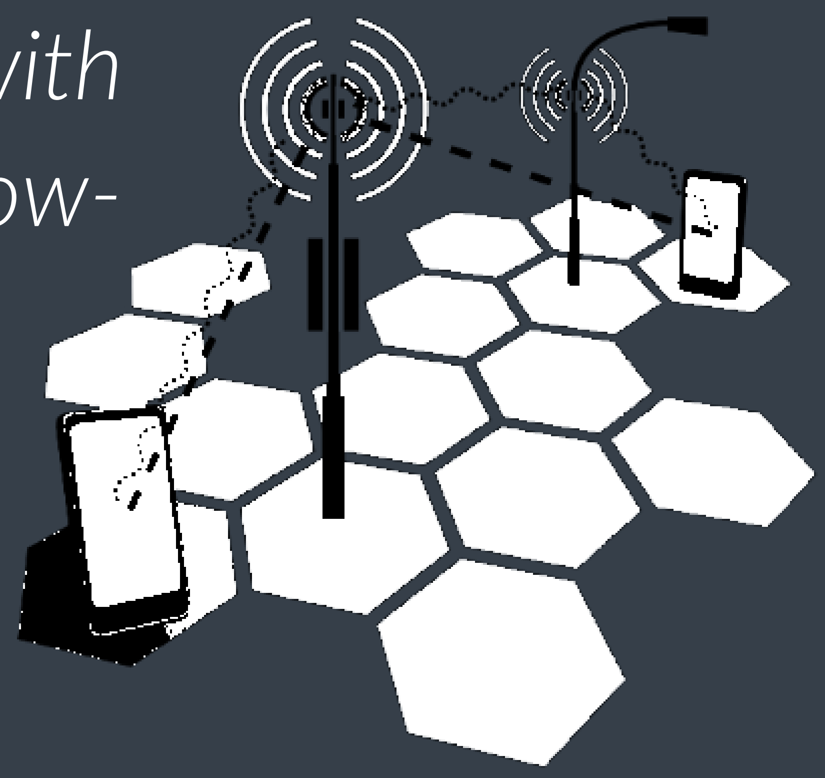




Problem 1: *Lack of on-chip mmWave BPFs.*

Problem 2: *Processing large bandwidths with low-latency and low-power.*





Challenges: size, cost and power consumption. Unfit for small cell/MIMO.

BULKY FRONT ENDS

Wavence

networks.nokia.com/products/wavence

Mini-Link

https://www.ericsson.com/en/portfolio/networks/ericsson-radio-system/mobile-transport/microwave/all-outdoor-shorthaul

RTN-380

http://carrier.huawei.com/en/products/wireless-network/microwave/e-band

GX4000

https://www.fujitsu.com/us/Images/GX4000-ds.pdf

iPASOLINK EX

https://www.nec.com/en/global/prod/nw/pasolink/products/ipasolinkEX_solution01.html

EtherHaul

https://www.siklu.com/product/etherhaul-kilo-series/

⋮

Nokia Networks

ERICSSON

HUAWEI

FUJITSU

NEC

Siklu

⋮

DragonWave, E-band communications, Ceragon, Intracom, Airspan, Cablefree, Siae Microelectronica, Lightpointe

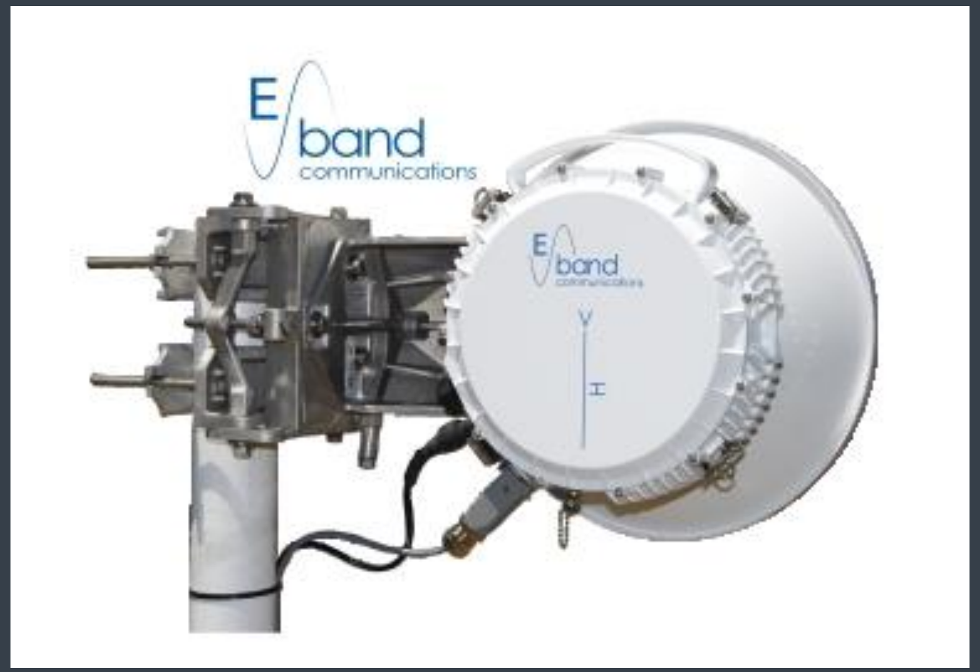
BULKY FRONT END PROBLEM

SMALL CELLS

No viable solutions at E-band for true Small Cell densification

1. Small Cell

Existing solutions: E-band



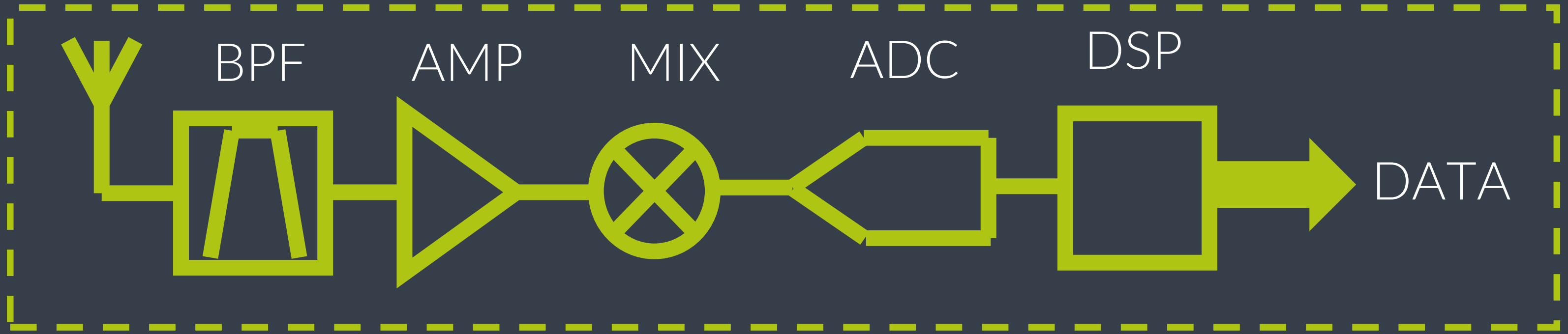
- $11k per link
- > 1m² real-estate
- ~ kW of power

X1 Every 50m² = Many MILLIONS

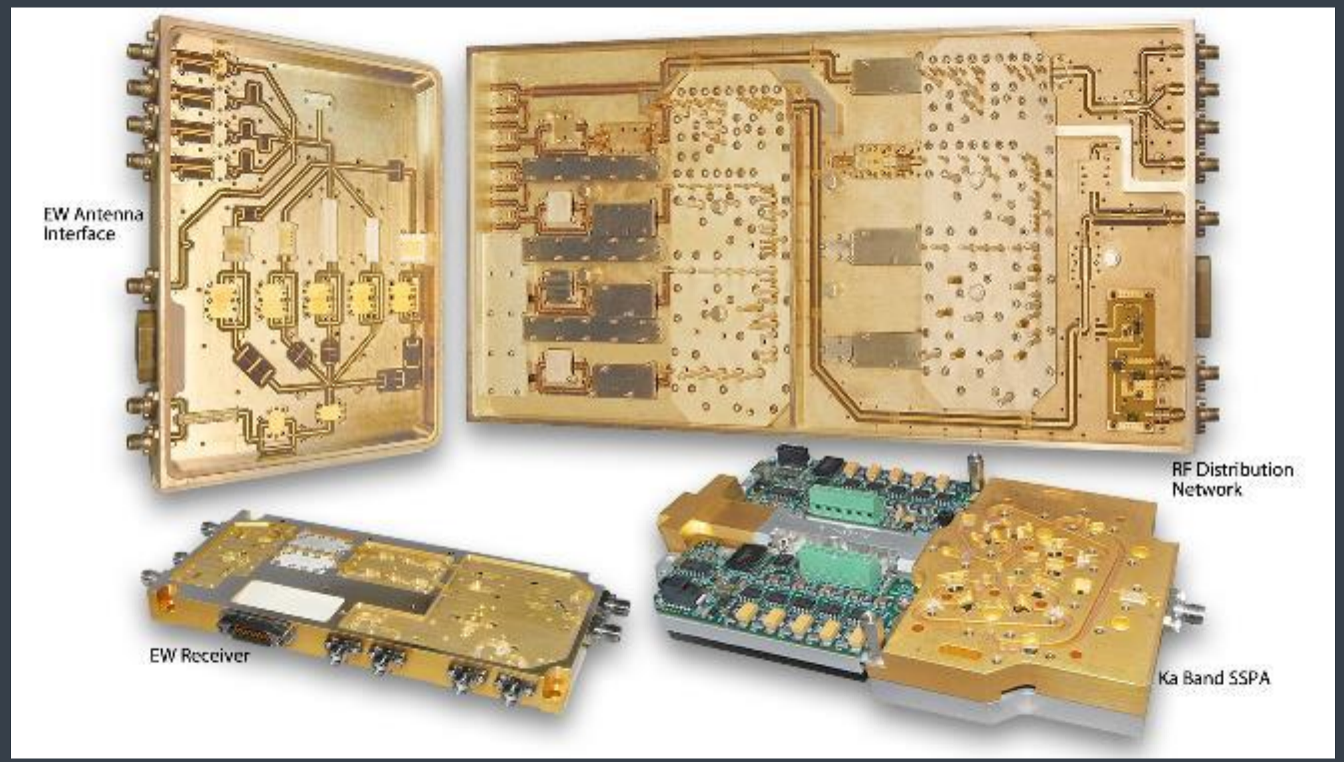
- $ Many Billions
- Millions m² real-estate
- ~ MWs of power

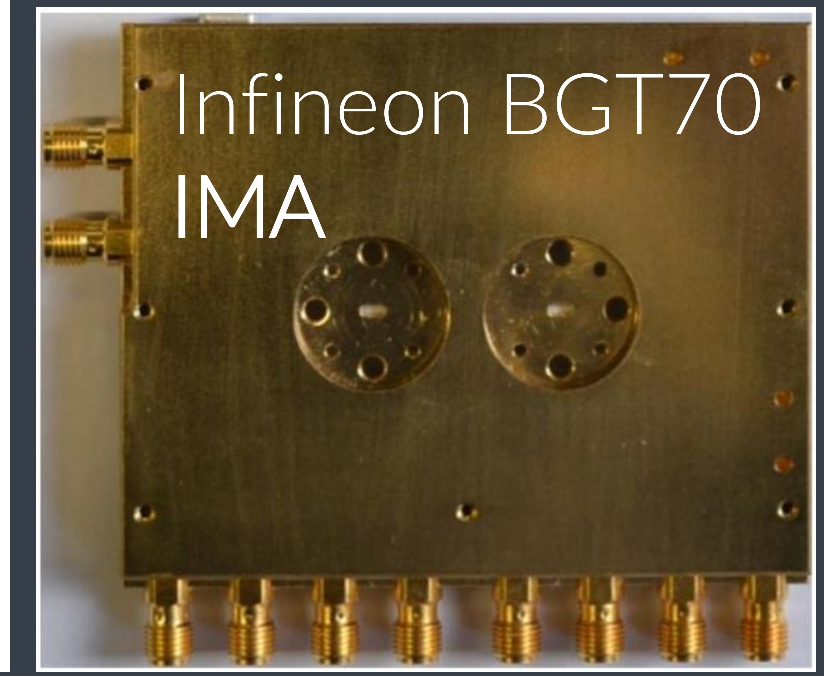
impossible

$$$$$$$



Integrated Microwave Assembly (IMA) → $$$$





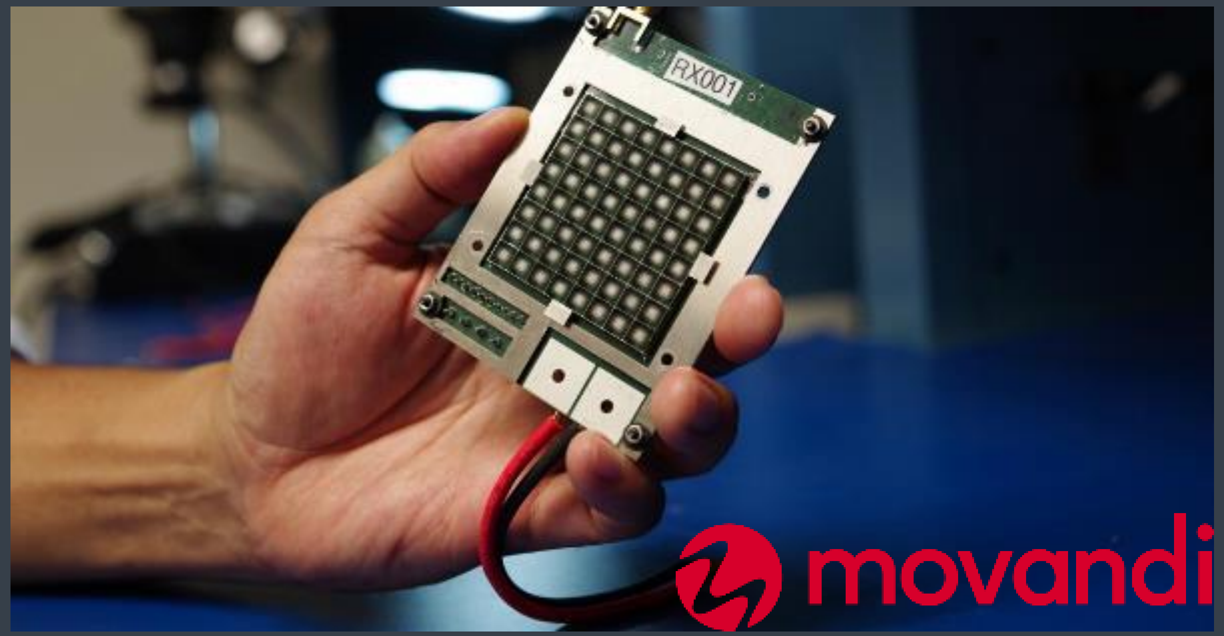
BULKY FRONT END PROBLEM

MMIMO

No solutions at E-band

Existing solutions: 28 GHz, 39 GHz

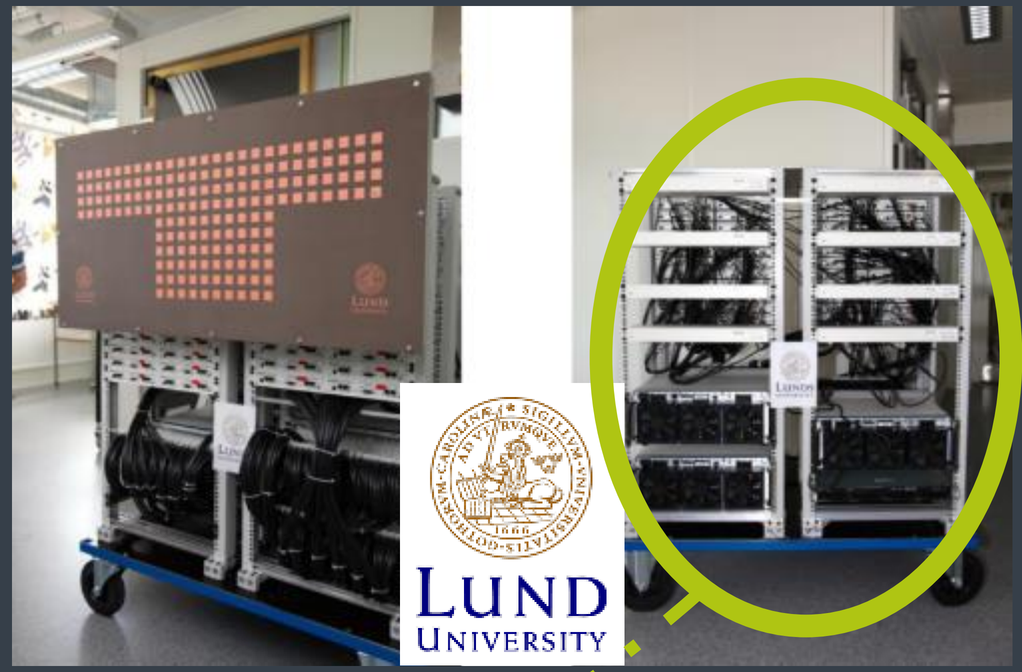
2. MMIMO



A solution like this is needed!

vs.

Existing solutions: < 6GHz

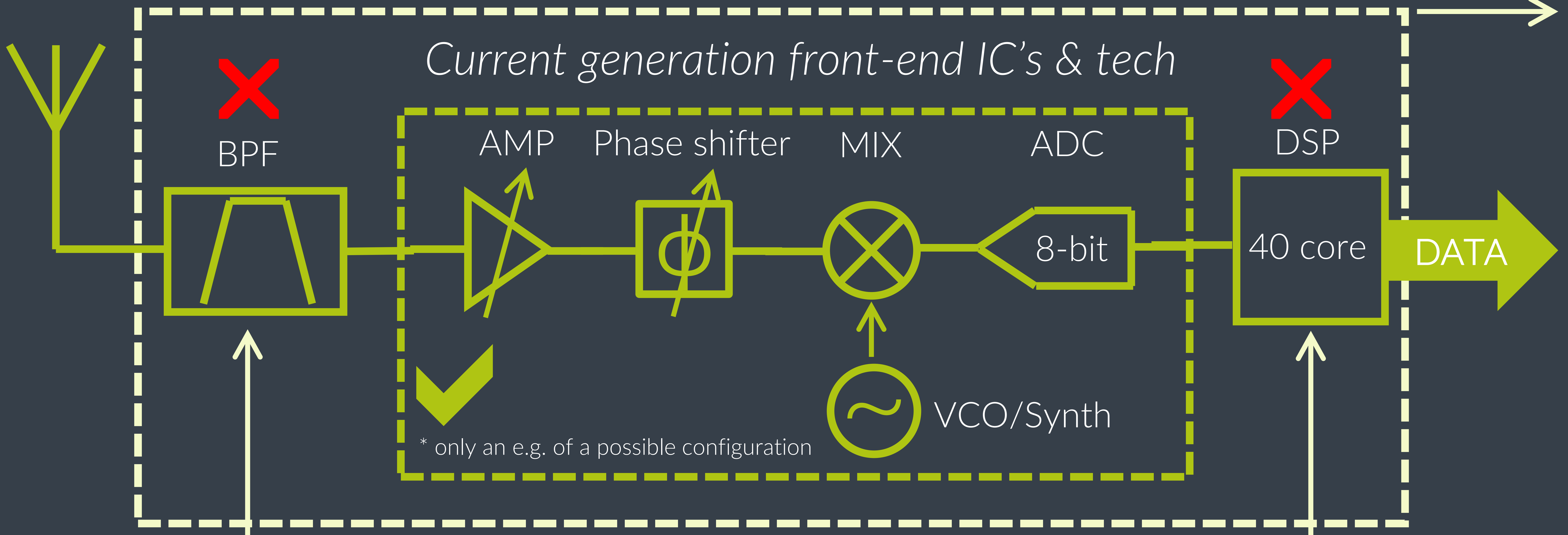


Real-estate? Power? $$$$?

Bulky, expensive, power hungry
→ No-go

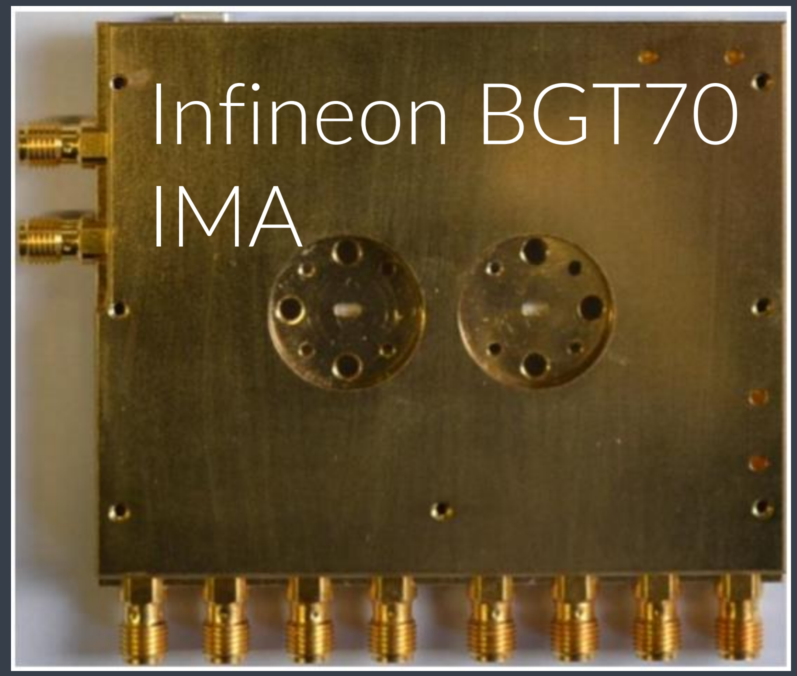
SUMMARY OF EXISTING SOLUTIONS

Size of a shoe-box

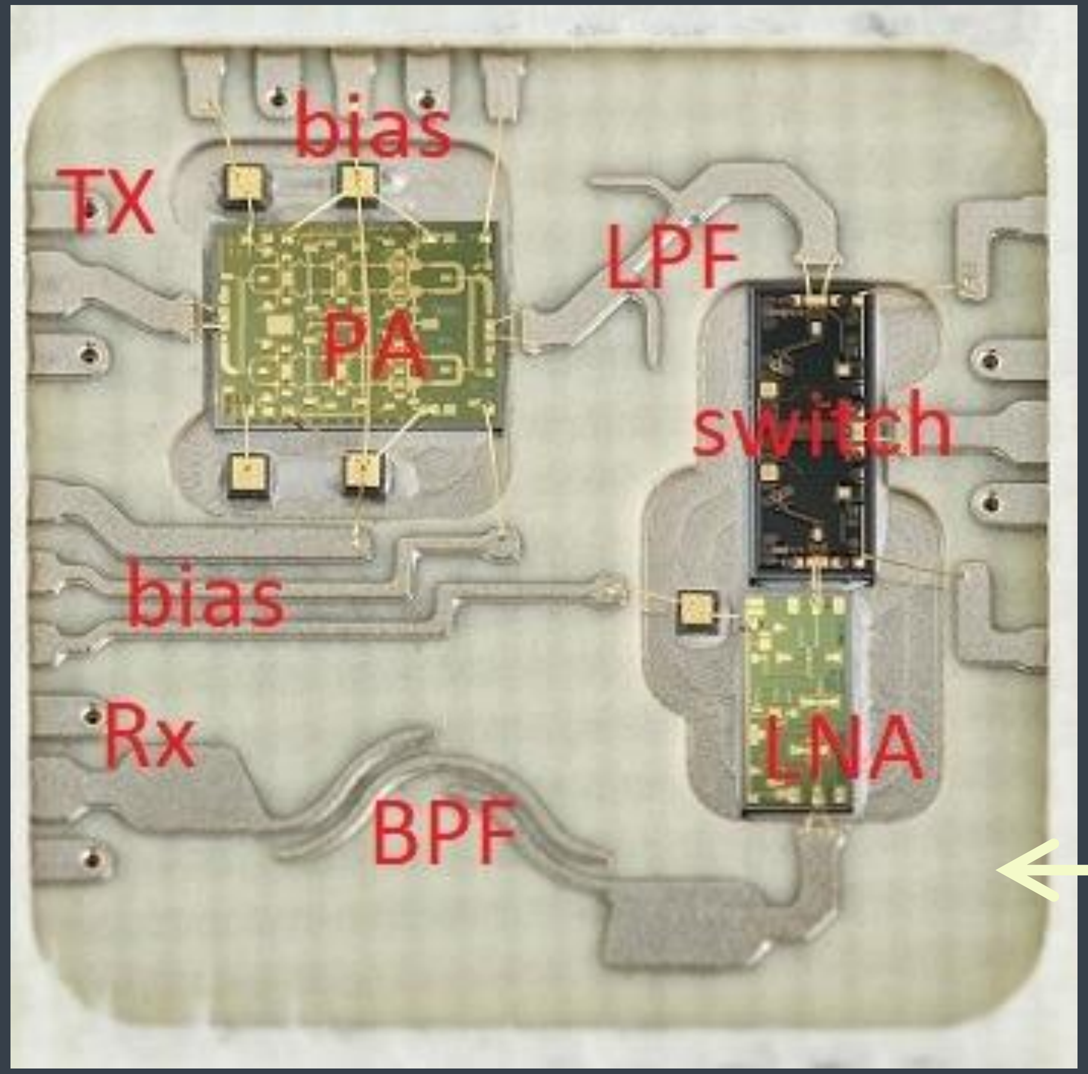


IMA (Integrated Microwave Assembly)

- *Thousands of $*
- *Manufacturing difficulty*
- *Low volume*
- *Power hungry*
- *Big and bulky*



SAW, BAW, waveguide (off-chip) – integration problem



IMA

Big-data problem

"mmWave will never materially scale beyond small pockets of 5G hotspots in dense urban environments"
-- T-Mobile CTO Neville Ray

"We will need to remind ourselves, this is not a coverage spectrum"
-- Verizon CEO Hans Vestberg

"The roll-out of 5G in the country will be much more case-based"
-- MTN South Africa CEO Rob Shuter

Millimeter-wave 5G isn't for widespread coverage, Verizon & T-Mobile admit

NO SMALL CELL OR MMIMO E-BAND SOLUTION IN SIGHT FOR MAJOR INDUSTRY PLAYERS!

↓

verizon

Built on 5G Challenge

What we're looking for.

Challenge areas

We're looking for solutions in the categories of Industry (helping businesses create new value for customers), Immersive Experiences (next-generation media and entertainment), and Moonshots (solving big problems with radical new ideas). Every submission should demonstrate the company's commitment to social responsibility and sustainable business practices.

Basically: they want apps that will make customers use their networks

OUR SOLUTION

We will make E-band connectivity so cheap and small it fits on every lamp-post!

OUR SOLUTION – INTEGRATION IN SILICON

- Cheap
- Mass producible
- Low power
- Small

Second generation

First generation

Thousands of $ (IMA)

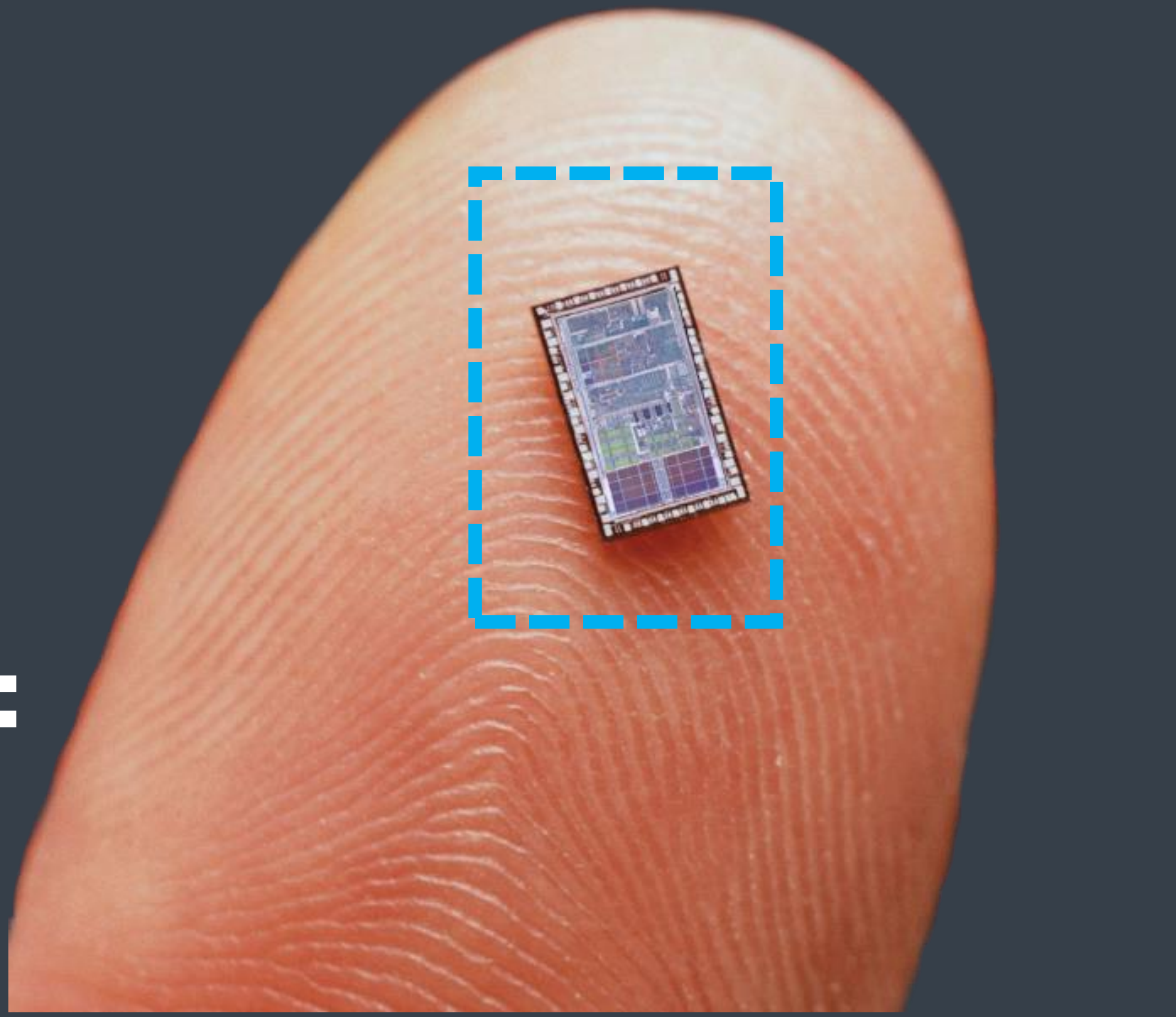
+

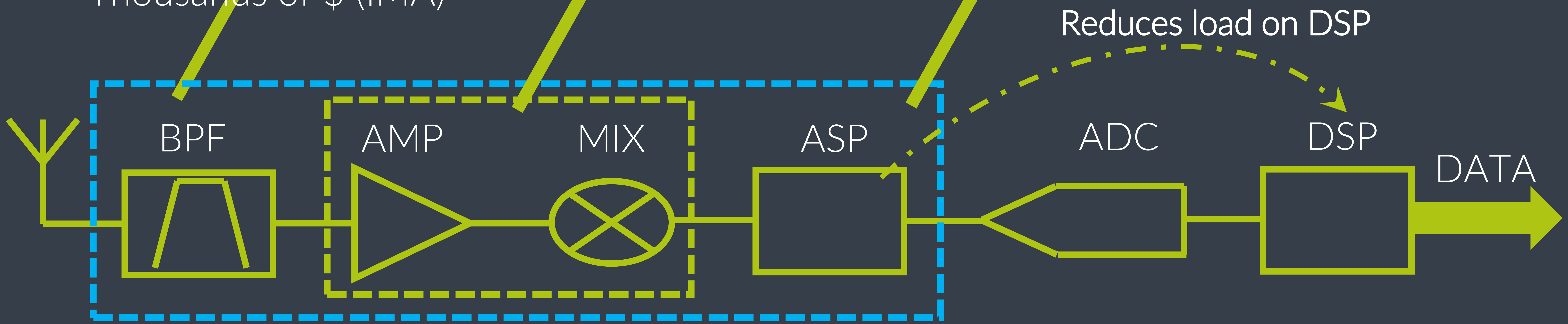
$63

+

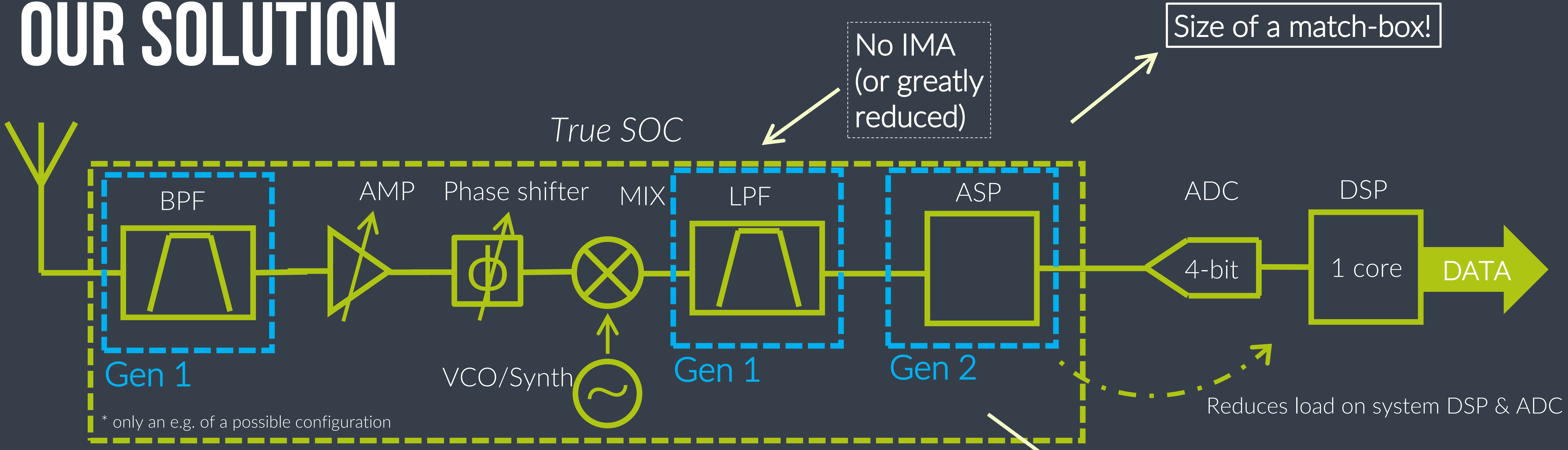
Thousands of $

=





OUR SOLUTION



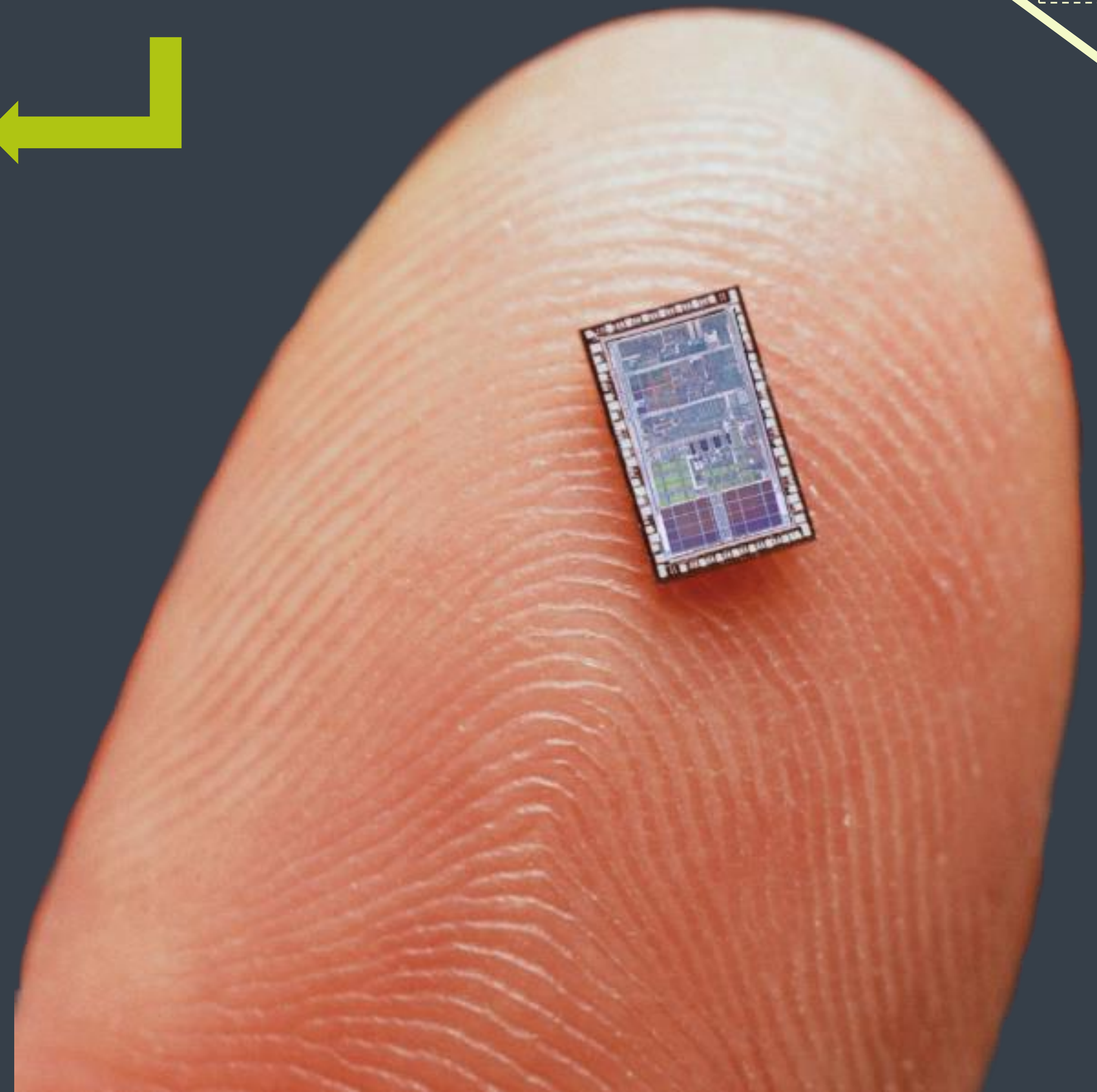
Our BPF & LPF is in Silicon (gen 1)

Our new ASP (gen 2)

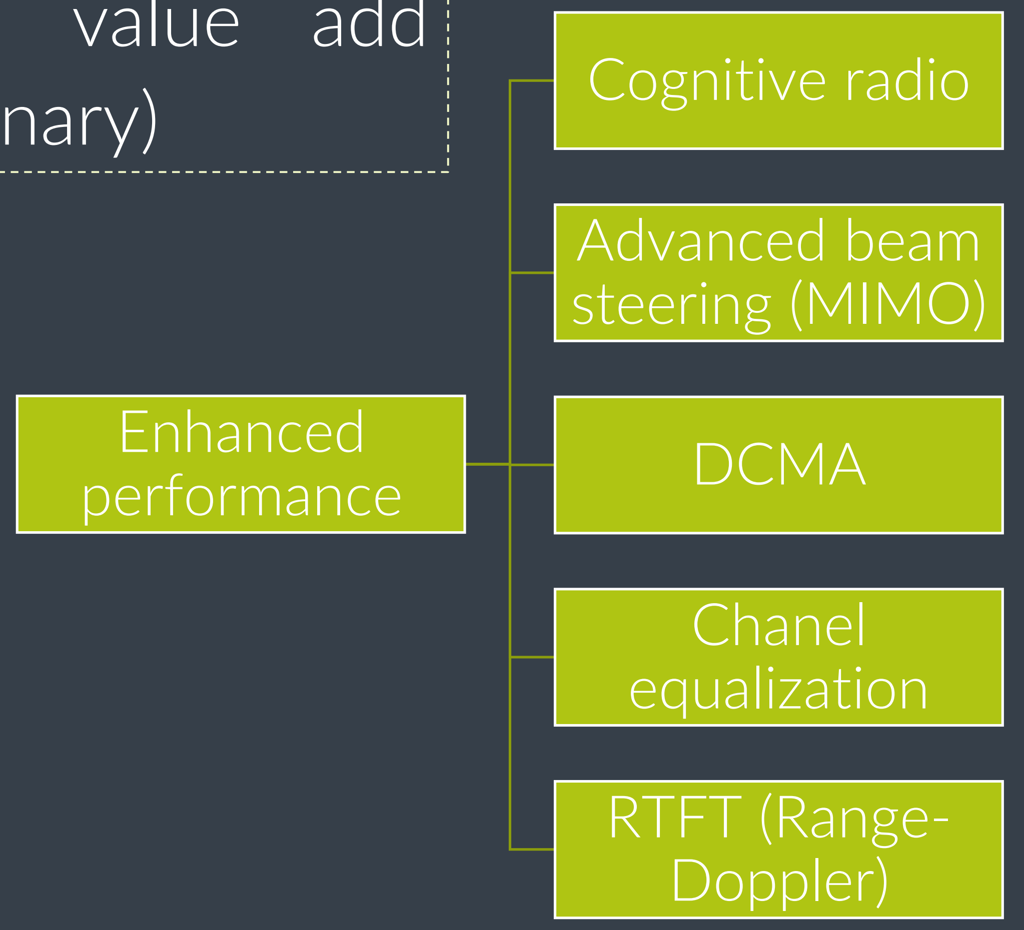
Stage 1: value add (evolutionary)

No/less IMA:

- Mass producible
- Cheap
- Small
- Low power
- Single chip
- Perfectly suited for Small Cells and massive MIMO
- Enhanced performance



Stage 2: value add (revolutionary)

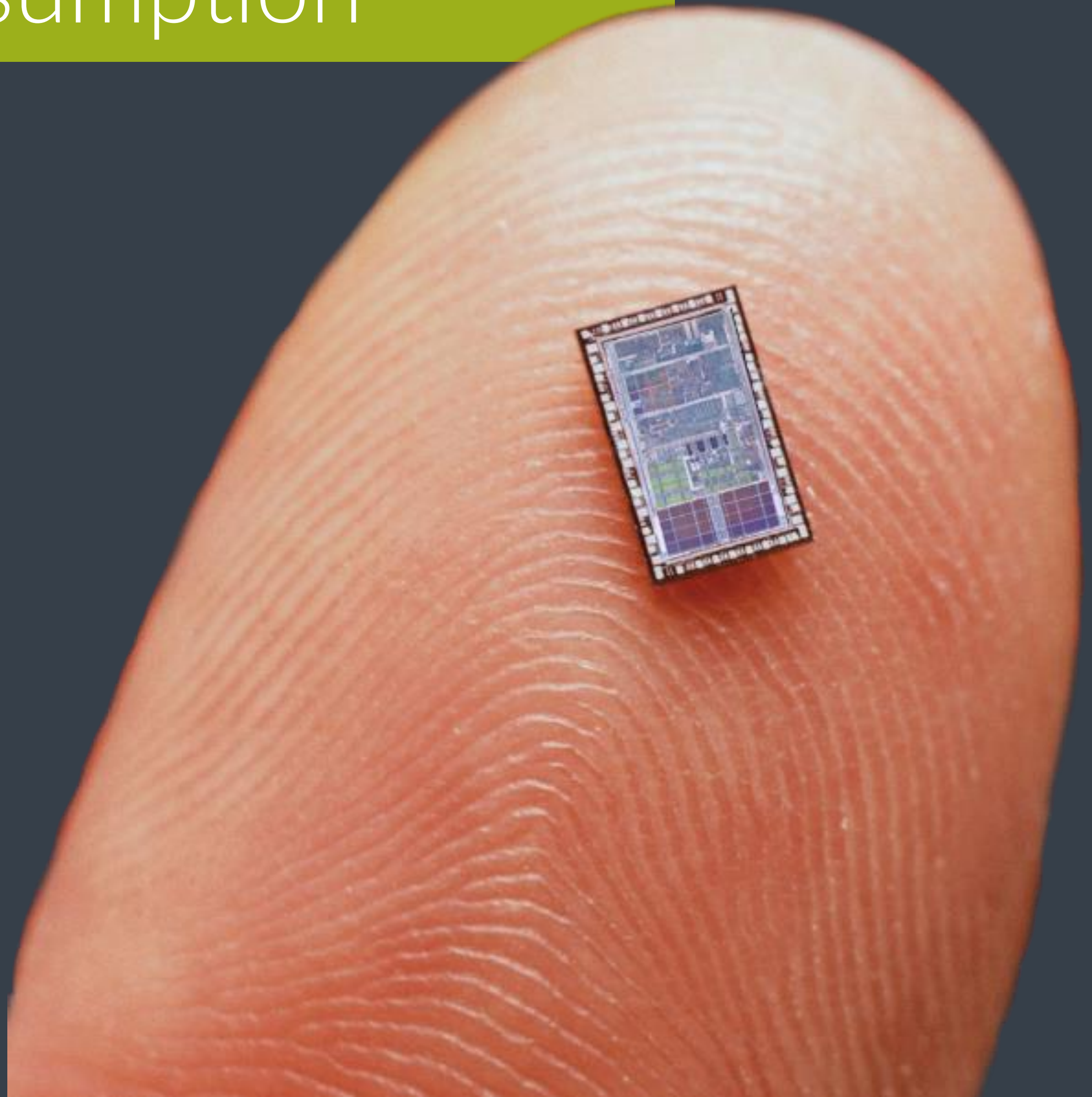


END PRODUCT COMPARISON

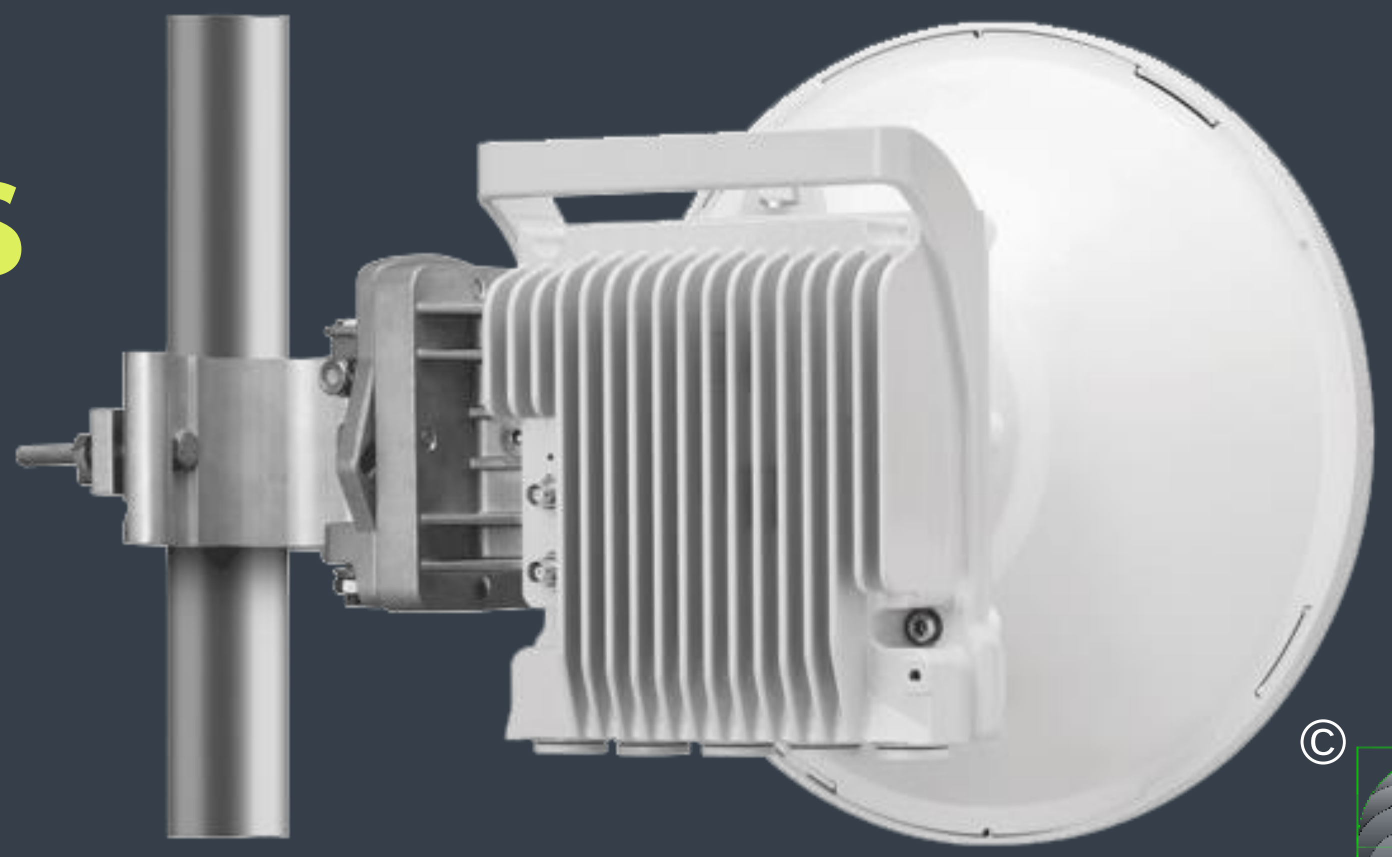
1. Single-chip TxRx front-end
2. With integrated tunable BPF
3. With analog signal pre-processing
4. This reduces size, cost and power consumption

We will make Gbps connectivity so cheap it will be on every light pole!

Cheap (< $1000)	Expensive (~ $11,200)
Low-power (<< 20 W)	Power intensive (~ 100 W)
Small (< 5 cm x 5 cm)	Bulky (~ 25 cm x 25 cm)
Mass producible	Low-volume



versus



*not to scale

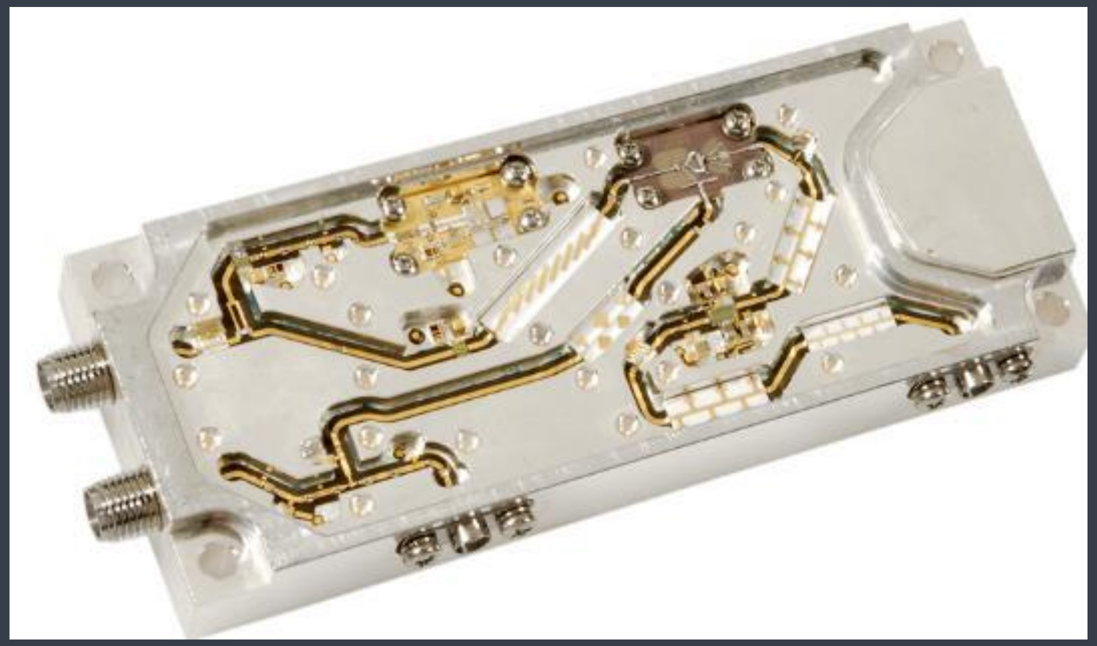
VALUE PROPOSITION

VALUE PROPOSITION

1. Silicon BPF

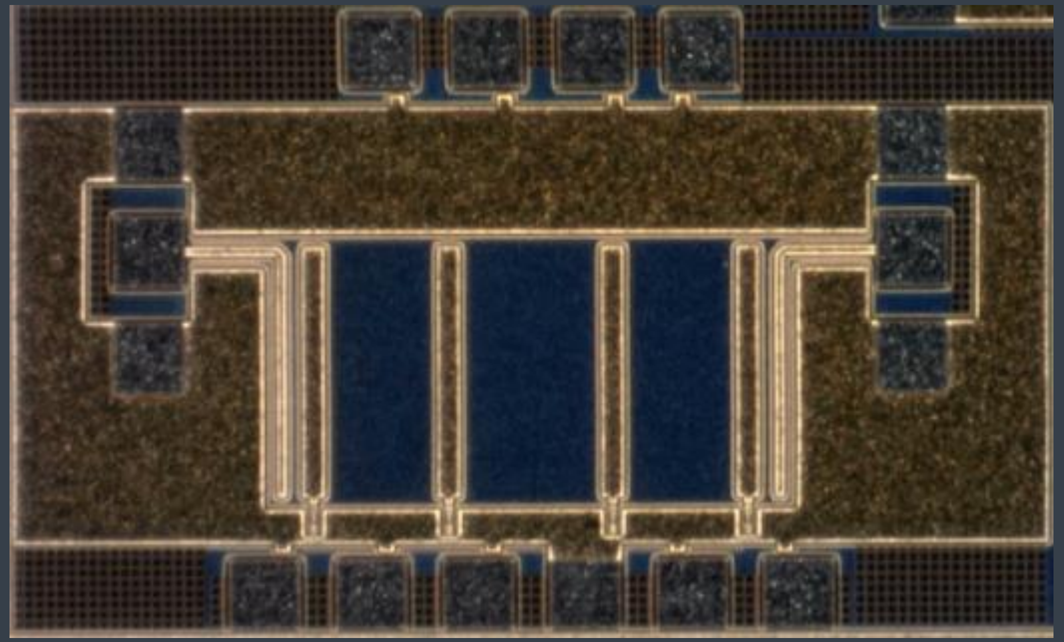
Existing solution

5 cm

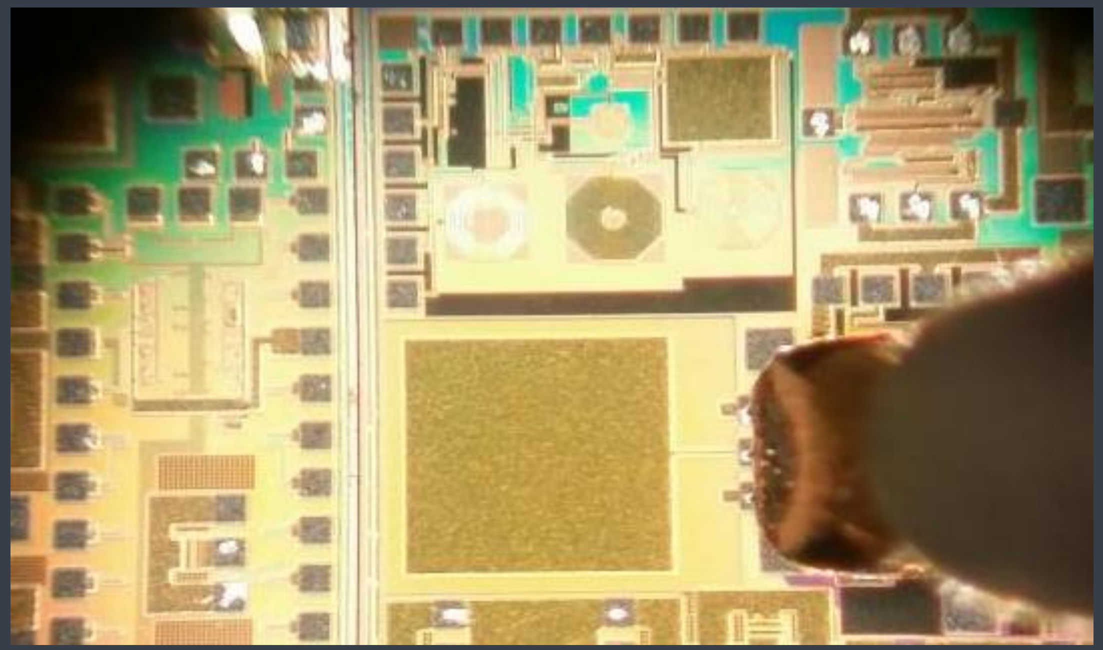


20 cm

Our solution



300 microns



1 mm

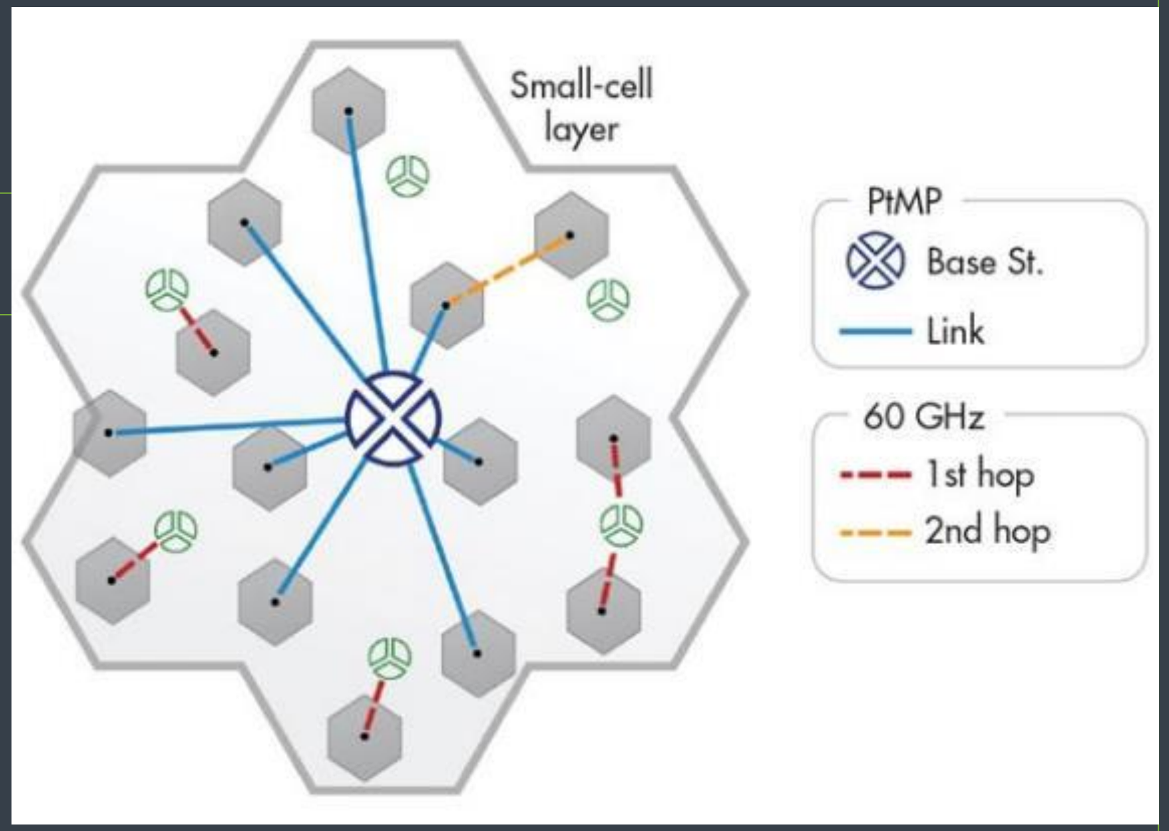
- Size & mass reduction x 100
- Monolithic integration enabled
- BOM reduction from
  - (2-8 individual filters)
  - (8-50 connectors and fasteners)
- No more hand tuning
  - Mass producible (easy to meet market demand)
  - Built in self tuning (BISTu)
- Cost benefits (IMA) – can be thousands of $ per unit

VALUE PROPOSITION

2. ASP: Real-time Fourier analysis for cognitive radio

- Real-time
- No need for FFT
- Large scanning bandwidth
- Low power
- Low-cost

Multifractal’s solution	SOTA
Instantaneous analogue Fourier transform of a 3 – 9 ns sample window	Computation time on the order of µs - C674x DSP: 256-pt FFT (16-bit) – 1.55 us, 512-pt FFT (16-bit) – 3.61 us
Frequency resolution < 0.5 GHz @ Δτ = 3 ns: • 0.3 GHz @ Δτ = 6 ns • 0.1 GHz @ Δτ = 12 ns	
Continuous bandwidth of 5 GHz per channel	Few hundred MHz
Dynamic range > 35 dB: @ Δτ = 3 ns: • > 40 dB @ Δτ = 6 ns • > 50 dB @ Δτ = 9 ns • 50+ dB @ Δτ = 12 ns • Noise considered	~30 dB
Power consumption ≈ 0.1 W (ADC) + ASP (< 50 mW) + x (mixer / mult) + x (LNA x 2) + x (envelope detector)	kW
Cost: soft substrate – few hundred $	Thousands of $
Cost: on-chip → cheap CMOS or BiCMOS (few cents per chip mass production)	-



E.g.: Cognitive Radio

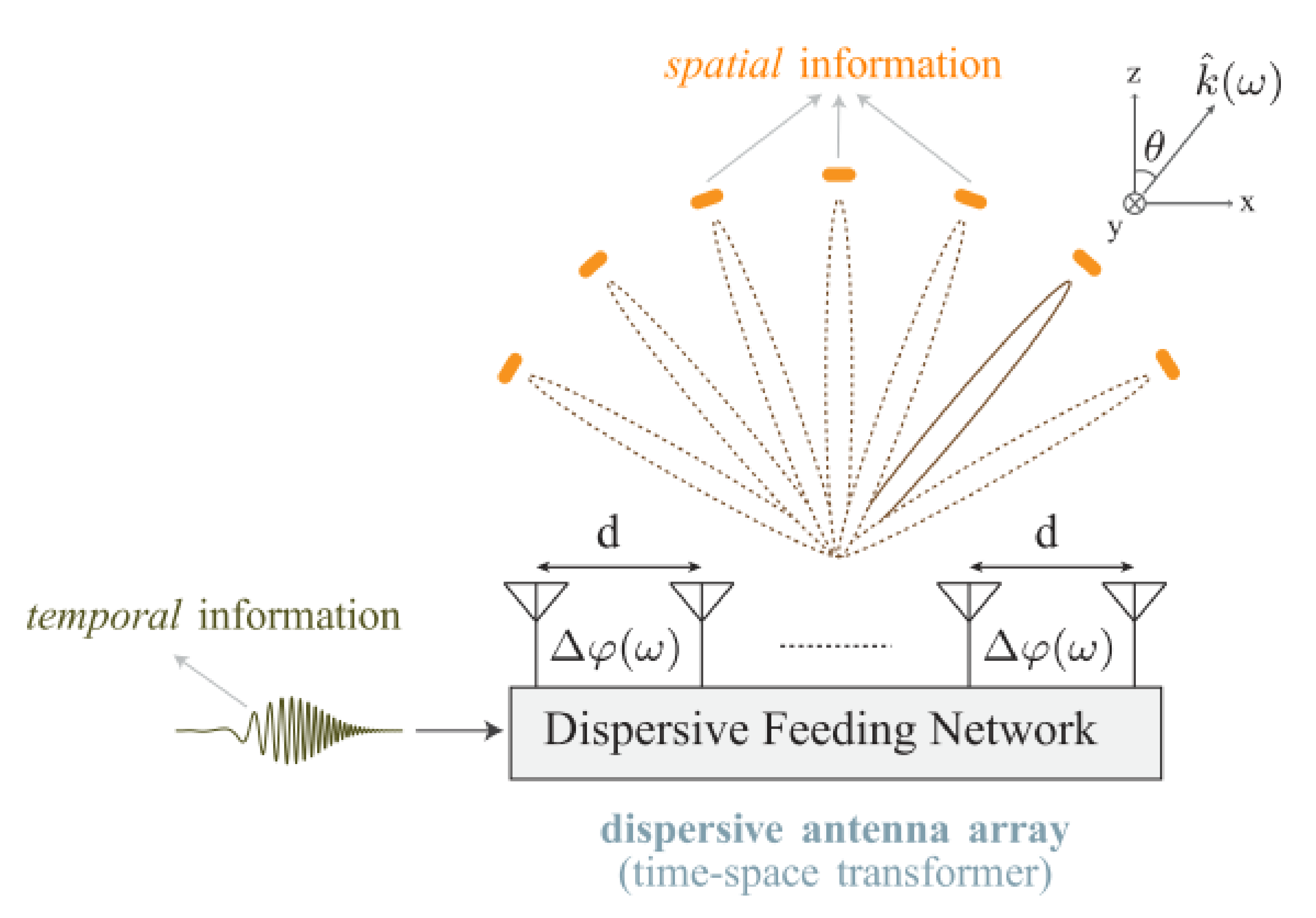
E.g.: Automotive radar

SOTA: resolution of 1m, maximum velocity of 30 m/s, few objects

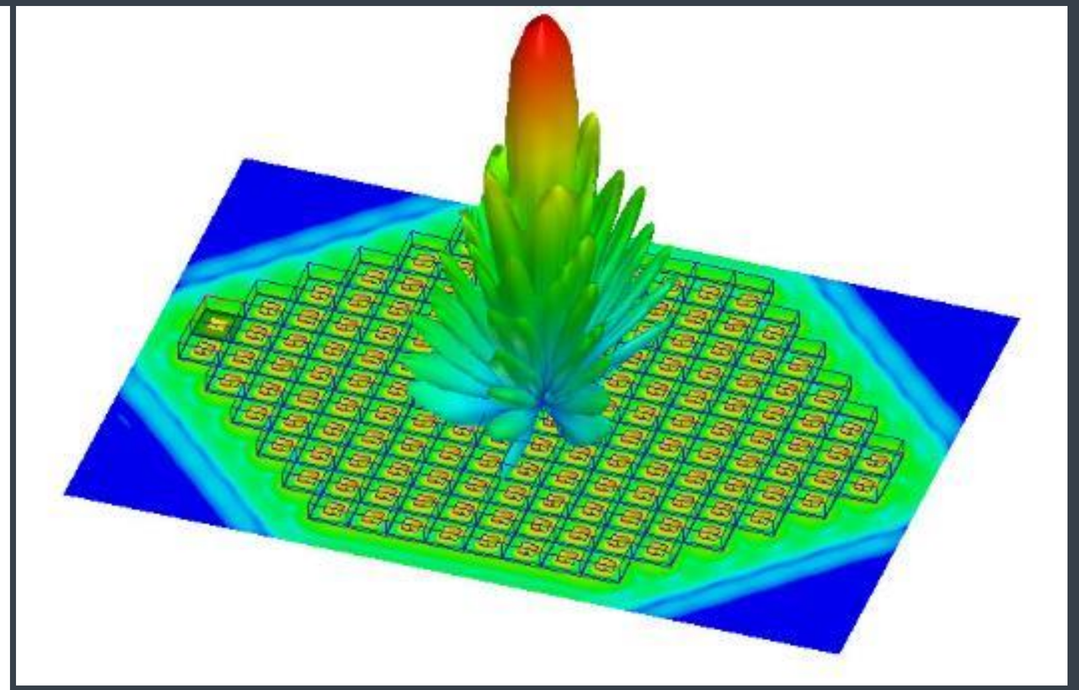
VALUE PROPOSITION

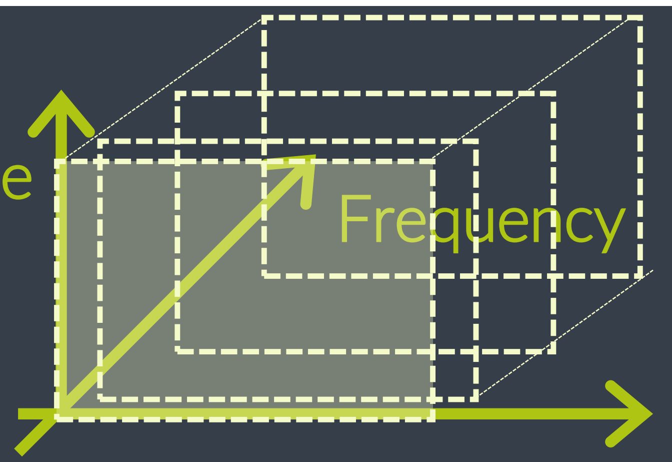
3. ASP: Advanced beam forming

- Arbitrary frequency beam steering
  - Steering angle controlled by frequency (carrier)
  - Continuously tunable (1 GHz BW -> 60 deg)
  - Specialized frequency to beam angle mapping possible
  - Low power – 20 mW per phaser (much lower than DSP solutions)
  - Low cost – CMOS and BiCMOS – support mass production



Even more Massive MIMO





Automotive radar

Multiple objects – SOTA 32

Wideband DDS can easily allow 60 deg to be mapped over 10 GHz allowing > 200 objects to be mapped each with 50 MHz fc control range

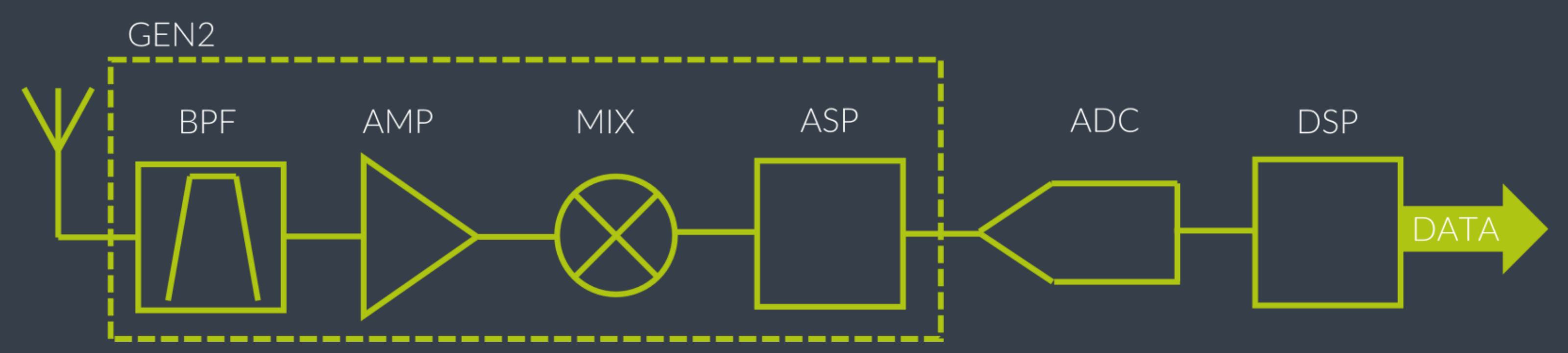
GENERATION 1 FRONT-END (telecoms)

High-level specifications

Parameter	Multifractal's gen 1 front-end	Siklu E-band front-end (EtherHaul 8010FX)	Our value add
Power consumption	< 2 W	50 W (including DSP)	10-20X power reduction
Cost	Tens of $	~$ 11k	>100X cost reduction
Channel bandwidth	5 GHz	2 GHz	SoC solution – fewer components, higher bandwidth, lower power
Throughput	10 Gbps full duplex	10 Gbps full duplex (FDD)	-
RF bands	71-76, 81-86 GHz	71-76, 81-86 GHz	-
System gain	80 – 98 dB	64 – 93 dB	-
Range	300 m	2.73 – 3.7 km	Small cell densification
Operating temperature	-45 to +85°C ++	-45 to +55°C	Single chip solution – better temperature performance / match
Dimensions	~ 10 by 10 cm (with MIMO array) – RF module (~5x5 cm)	~ 30 by 30 cm (single antenna – no MIMO)	Massive MIMO
Weight	< 100 g	~ 5 kg	Small, lightweight
NF	~5 dB	?	Relxed requirements due to small cell dens.

Smaller range has benefits – our solution allows for this small cell dens. due to lower costs, power and size

GENERATION 2 FRONT-END (telecoms)

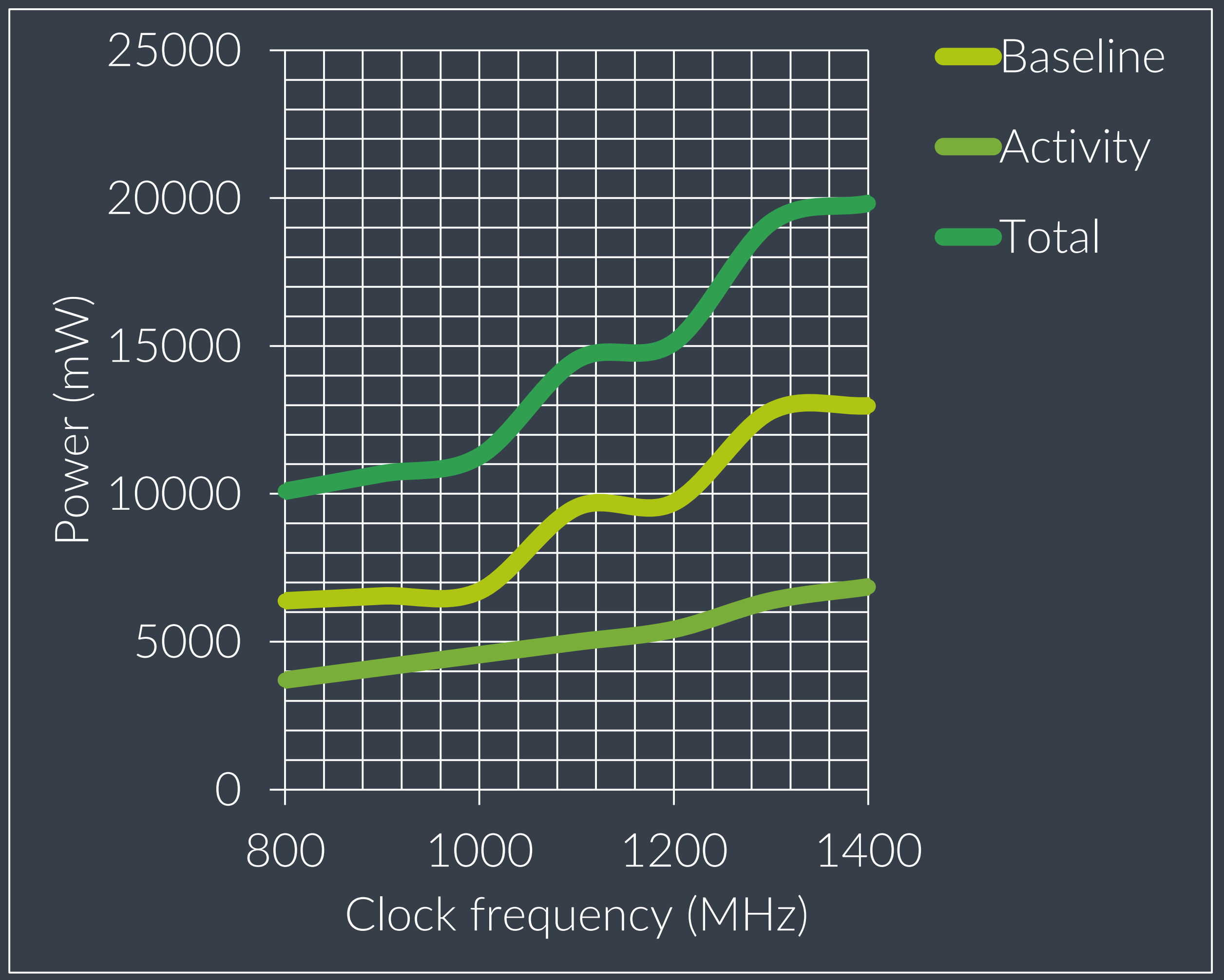


High-level specifications (ASP only – cognitive radio – other specs stay the same)

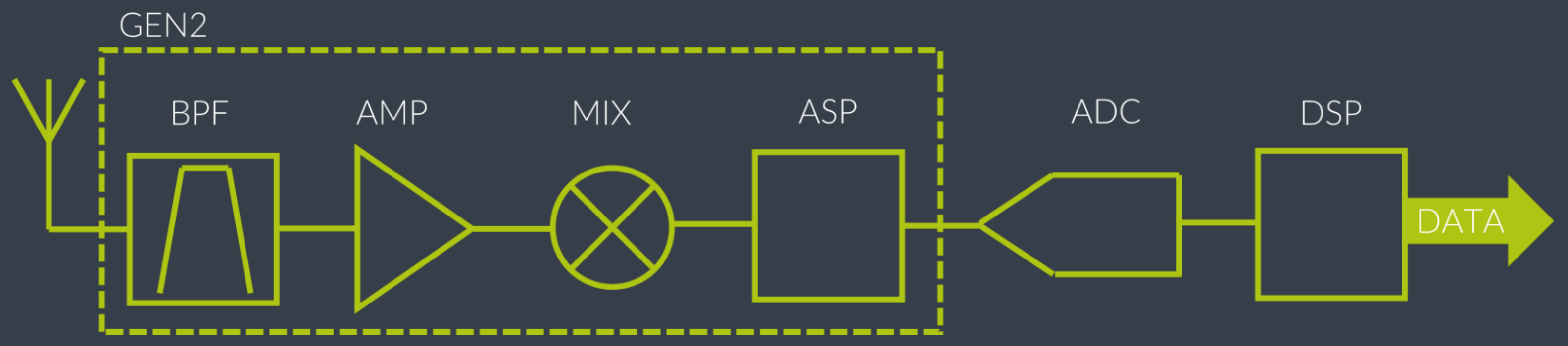
Existing solution do not scale well with bandwidth

Parameter	Multifractal's IC	TI's AWR1243 / DSP 66x series or equivalent	Our value add
Power consumption	< 20 W (incl. DSP)	> 100 W (incl. DSP)	5-10X reduction
Cost	Hundreds of $	Thousands $	>100X reduction
Processing speed	< 50 ns per FFT	> 1 µs per FFT (1 core)	50X improvement (faster multiple object detection)
IF bandwidth (automotive radar)	1-4 GHz	5 MHz	100X faster (faster detection)
RF bandwidth (automotive radar)	4 – 8 GHz	4 GHz	2X larger → 2X resolution (4.5cm → 2.25 cm)
Complexity	Final system design = simple/no IMA!	Final system design = complex IMA	Supports mass production, lower production costs
Dynamic range	50 dB	~50 dB	-
ENOB	4	8	Relaxed ADC requirements
Equivalent n-points	70 (current technology with the aim to improve)	-	-
Power accuracy	±3 dB	~ 1 dB	-
Frequency accuracy	~ 100 Mhz	~ 100 MHz	-
Magnitude / phase information	Magnitude only	Both	Application dependent

TI 66x (8 cores)

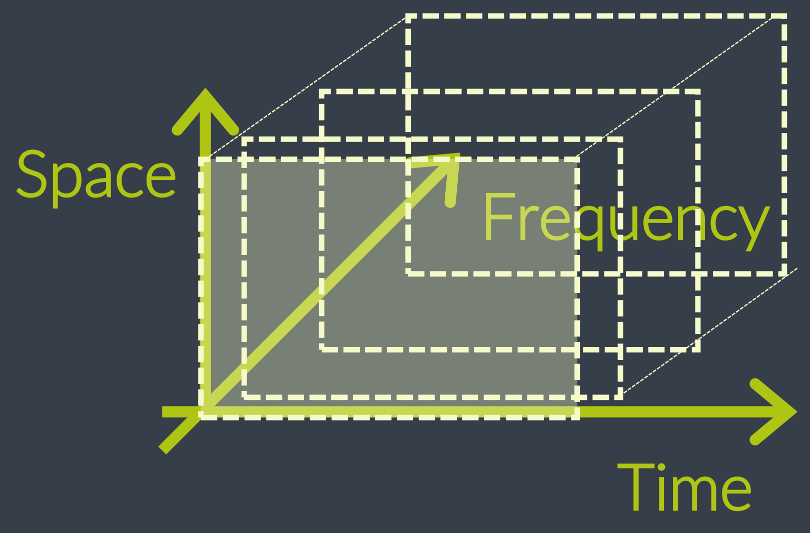


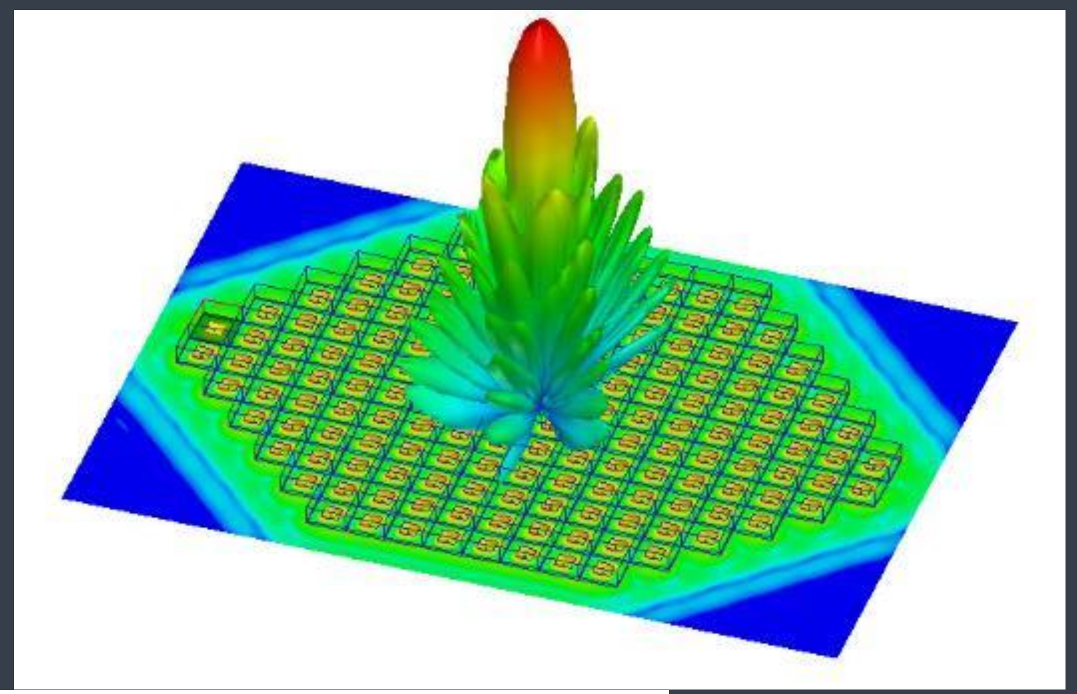
GENERATION 2 FRONT-END (telecoms)

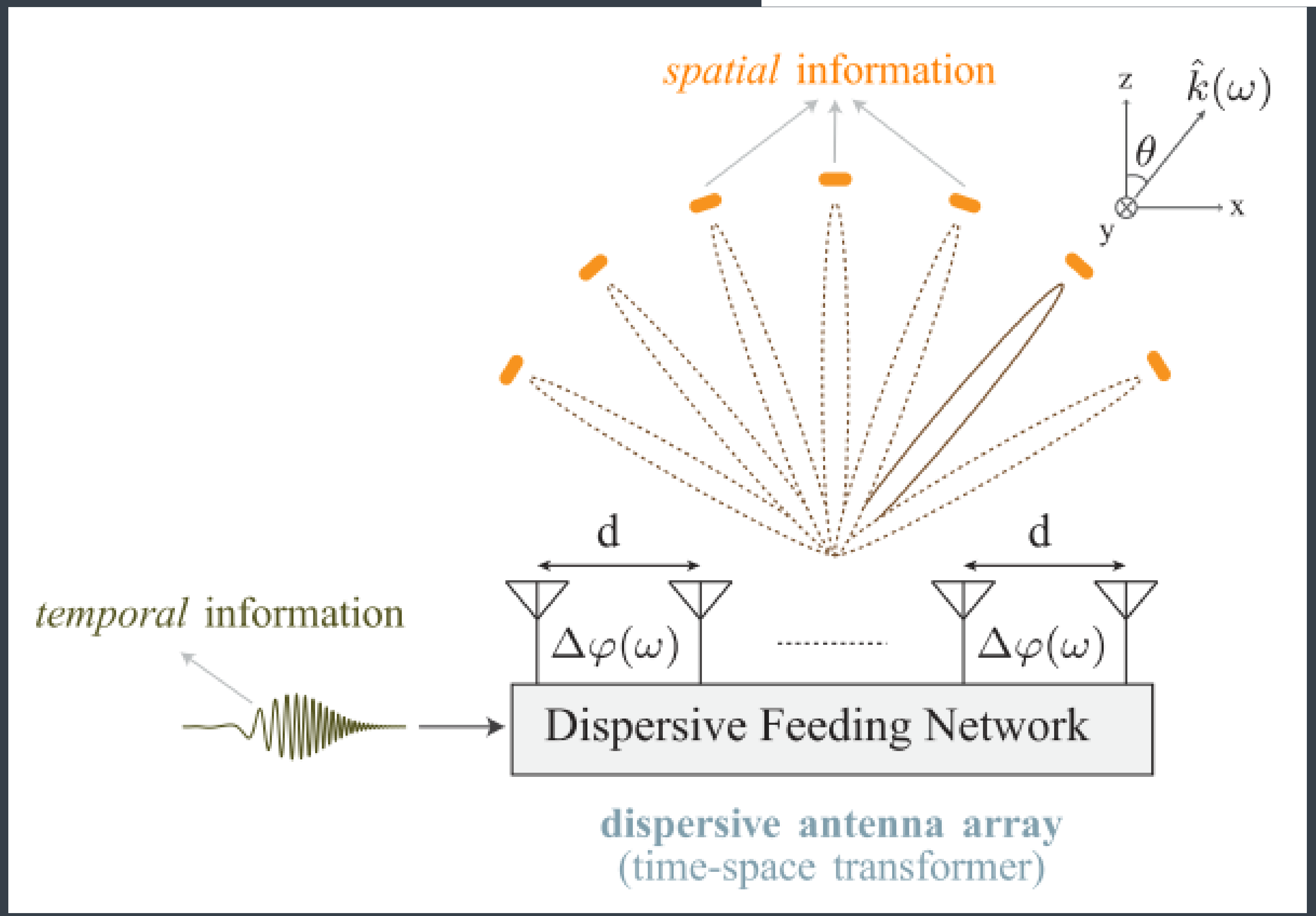


High-level specifications (ASP only – frequency beam steering – other specs stay the same)

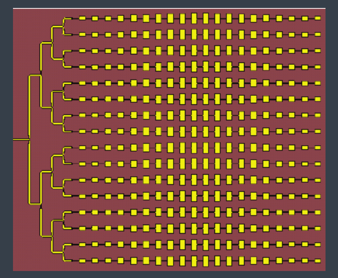
Parameter	Multifractal's IC	TI's AWR1243 / DSP 66x series or equivalent	Our value add
Power consumption	< 20 W (incl. DSP)	> 100 W (incl. DSP)	5-10X reduction
Cost	Hundreds of $	Thousands $	10X reduction
Processing speed (tracking speed)	< 50 ns per operation	> 1 µs per operation (1 core)	50X improvement (faster steering)
Complexity	Final system design = simple/no IMA!	Final system design = complex IMA	Supports mass production, lower production costs
Dynamic range	50 dB	~50 dB	-
Bandwidth	> 8GHz	4 GHz is already a challenge	
Channels per antenna (frequency mapped to angles)	> 30 (only one array! – one tile)	? (Unheard of) – many tiles / antenna arrays needed	More massive MIMO! Truly big data.
Frequency reconfigurability (lens effect)	8 GHz band → 100 MHz band	Unheard of	Frequency lensing



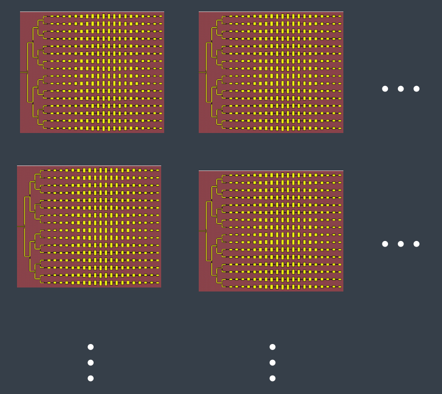




One array



vs



Many arrays

BUSINESS MODEL & EXEC

What we’ve done and where we’re going.

OVERVIEW & FOCUS

How will we make money?

Costs

- Design
- Manufacture
- Sales
- Distribution

Applications

- Communications
- Sensing

Markets

- 5G Backhaul & Fronthaul
- Fixed wireless access
- 5G Access
- Automotive radar

Products

- Full F/E as Chip
- Components as SiP
- Full F/E as SiP

Revenue streams

- Chip sales
- IP Licenses
- Services

KEY PROJECT SUPPLIERS & PARTNERS in the context of our value chain

EXECUTION TIMELINE

2014
Research began

2017
Proof of Concept & Incorporation

2018
Raising funding for product development

2020
First samples delivered to customers

2021
Full scale manufacture

EARLY CUSTOMERS & TRACTION

Interested in E-Band F/E for telecommunications.
LOI provided. Waiting for samples.

Siklu

Interested in E-Band BPF (& other F/E components) for single chip CMOS radar. LOI imminent. Waiting for samples.

arbe ROBOTICS

Interested in ASP for defence (analog FFT).
Paying $ 50 k for NRE.

Saab Grintek

Prospective:

ERICSSON, 5G Nokia Networks, BOSCH, SAFERADAR RESEARCH, SILICON radar, NEC, FUJITSU, HUAWEI

FUNDING TIMELINE

What has been done so far?

Bootstrapped
$ 10 k

2017

2018 Q1

GAP ICT & TelAviv SA
Winner
$ 20 k

SAAB NRE
$ 50 k
✓

2018 Q4

Confirmed – full support!

SILICON CATALYST
CA, USA

2018 Q4

✓

Si Catalyst in-kind support
$ 1.6 M

Almost finalized (term-sheet)

STARFINDER SEED CAPITAL FUND

VIGO SYSTEM

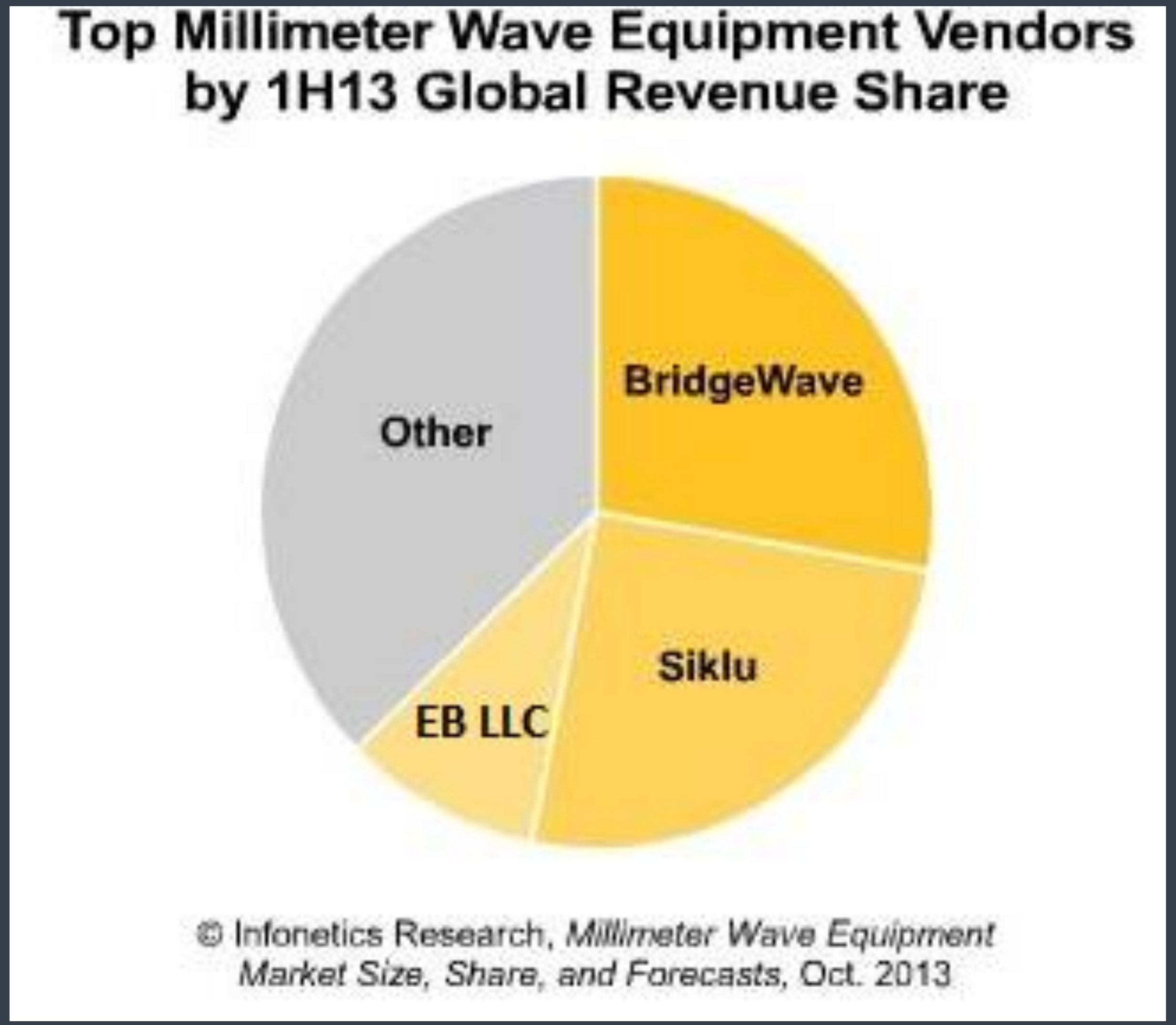
2019 Q1

StarFinder & Vigo Systems
$ 1.6 M

TEL AVIV NONSTOP CITY

FINANCIALS – MARKET PROJECTIONS (SAM)

Year	TAM	CAGR
2017	$400 000 000,00	38,85%
2018	$555 400 000,00	38,85%
2019	$771 172 900,00	38,85%
2020	$1 070 773 571,65	38,85%
2021	$1 486 769 104,24	38,85%
2022	$2 064 378 901,23	38,85%
2023	$2 866 390 104,36	38,85%



- Existing: single link = 10 000 USD
- Multifractal's disruptive product will bring single link down to 1000 USD
- Drastically raise the volumes shipped. Based on this:
    - our projections indicate a market share of 9.69% in year 4 growing to 15.08% in year 6

FINANCIALS – EXPECTED REVENUE (SOM)

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8
Theme	1. Lean development			2. Production ramp-up		3. Full - Production		
Objectives	1.1. Develop tech 1.2. Develop market 1.3. Produce and distribute samples			2.1. Develop product 2.2. Develop sales and distribution channels 2.3. Full wafer production		3.1. Grow market share 3.2. Grow product line		
Revenue	$0	$0	$0	$7,360,000	$19,200,000	$28,400,000	$33,950,000	$47,700,000
Costs	$555,579	$538,678	$514,646	$5,349,016	$8,064,634	$12,678,928	$15,063,663	$17,675,697
Profit	-$555,579	-$538,678	-$514,646	$2,010,984	$11,135,366	$15,721,072	$18,886,337	$30,024,303
Cashflow	$1,053,324	$514,646	$4,895,057	$6,906,041	$18,041,406	$33,762,478	$52,648,815	$82,673,118
Investment	$1,608,903		$4,895,057					
	Technology development			*Commercialization*				

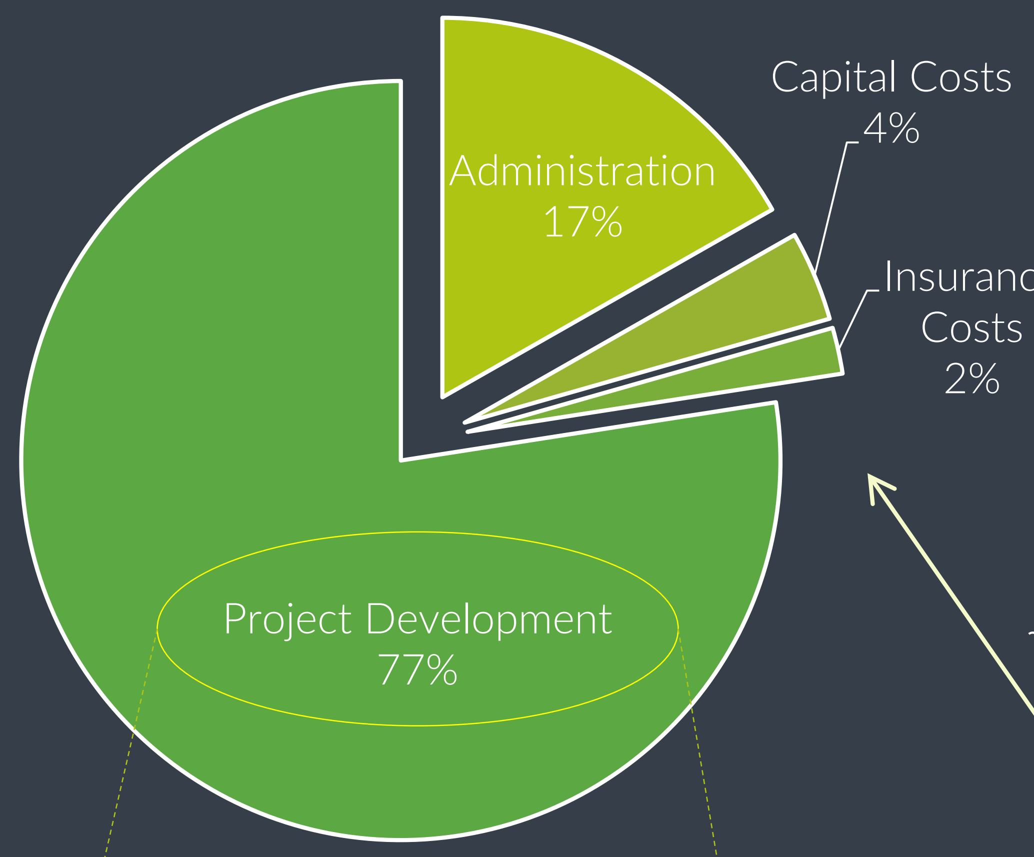
Tech development funding - $ 1.6 M

Commercialization grant - $ 5 M

QUARTERLY BUDGET

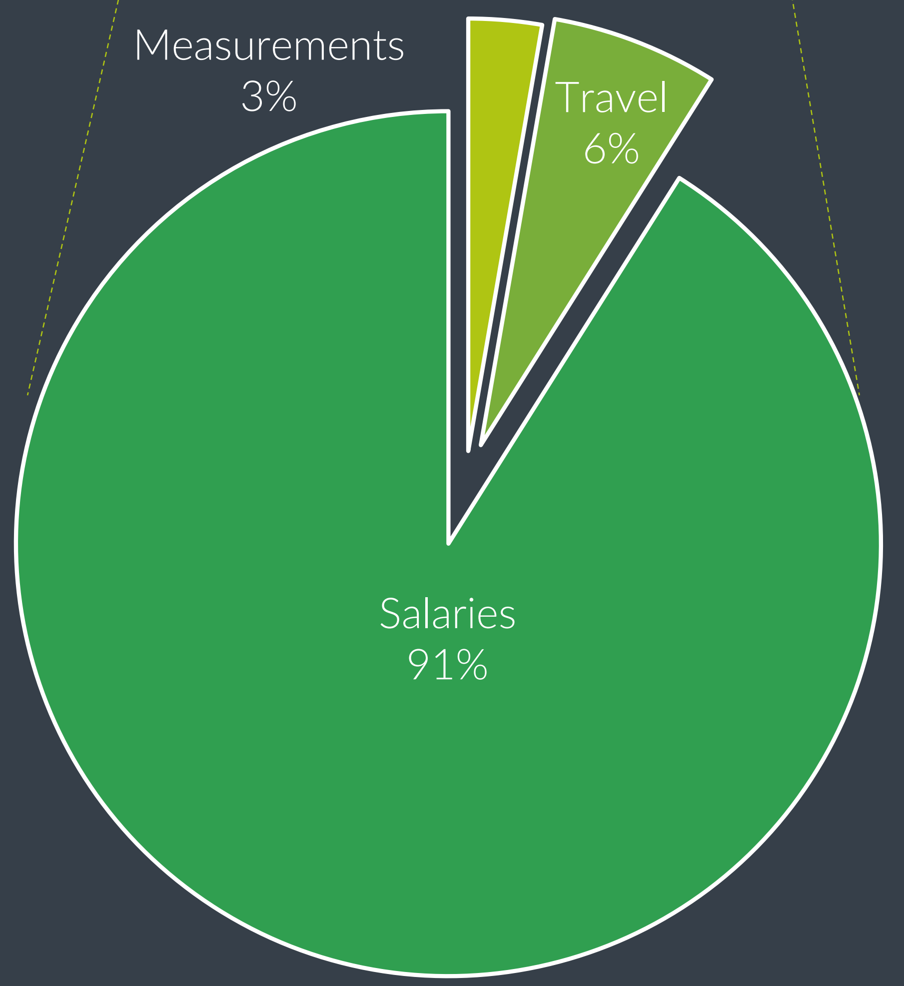
COMPARISON

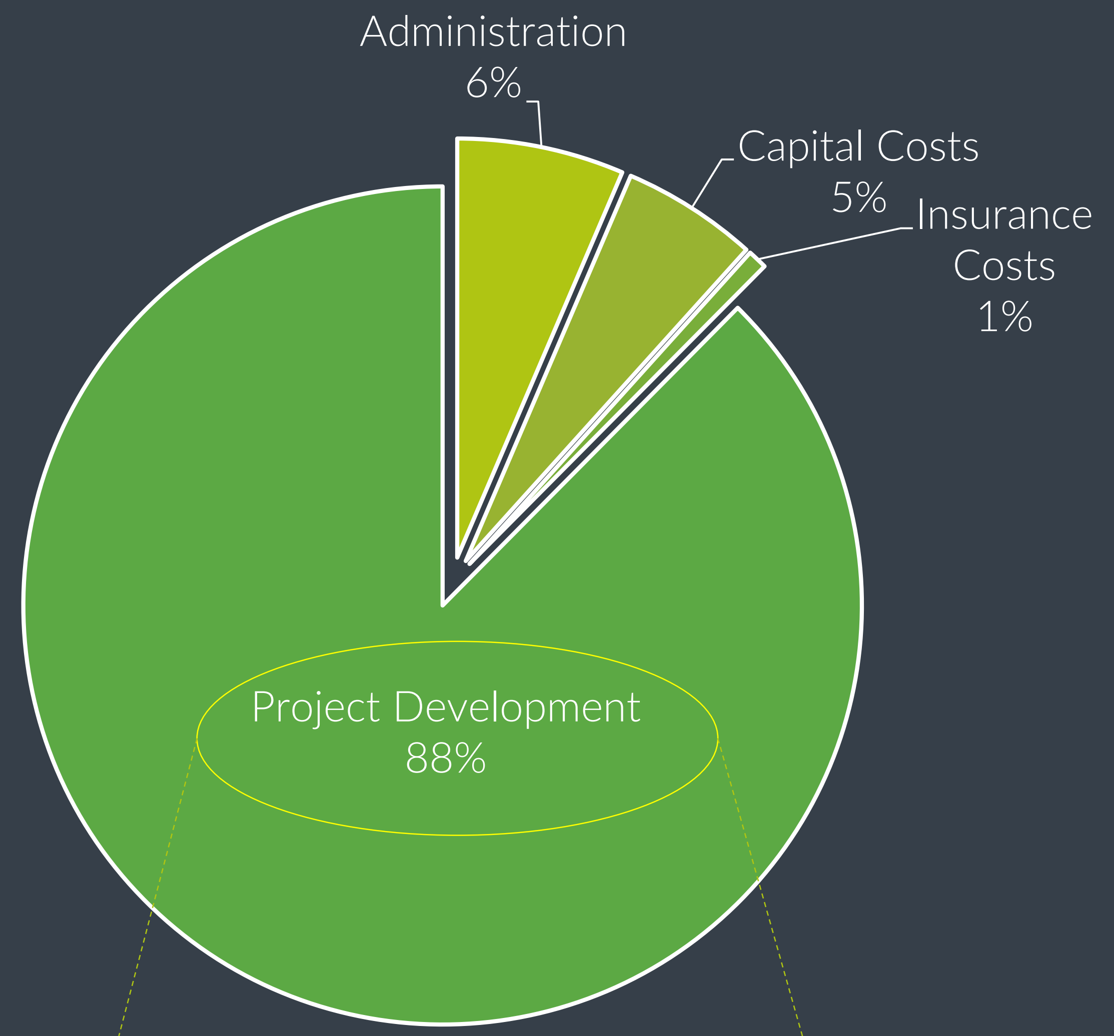
With Si Catalyst support	Without Si Catalyst support
Required minimum cash funding: ~ $1M	Required minimum cash funding: ~ $2.65M
Mostly salary & office space	Mostly EDA, prototyping & salaries



Office space ~$100k

Salaries ~$720k





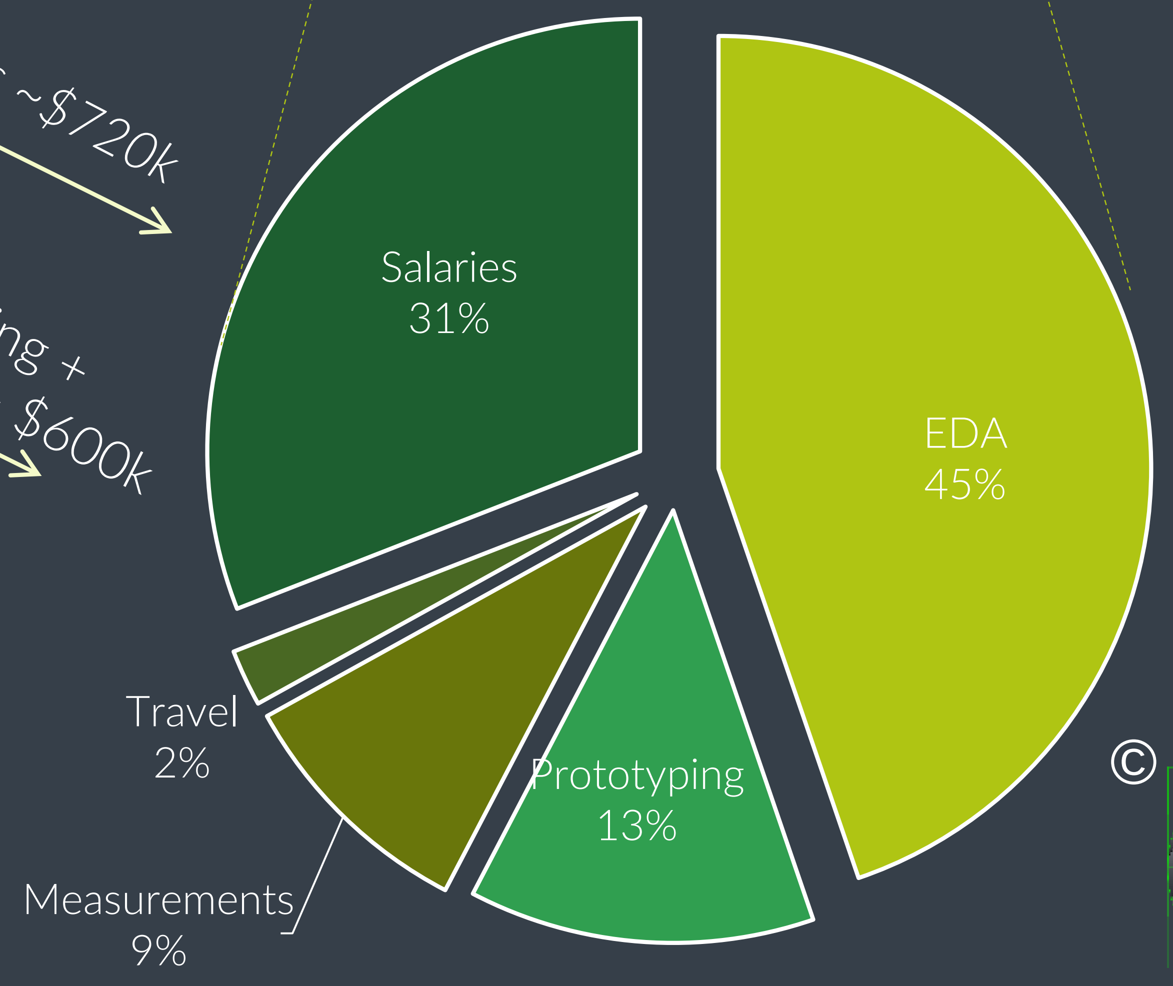
We had an offer in the past to this effect: i.e. it is possible

Assuming 80% discount for Synopsys/Cadence & 60% discount for Keysight ADS

EDA cost > $1M

Salaries ~$720k

Prototyping + measurement > $600k



→ Si Catalyst LLC equivalent necessary cash support ~ $1.6M

IP STRATEGY

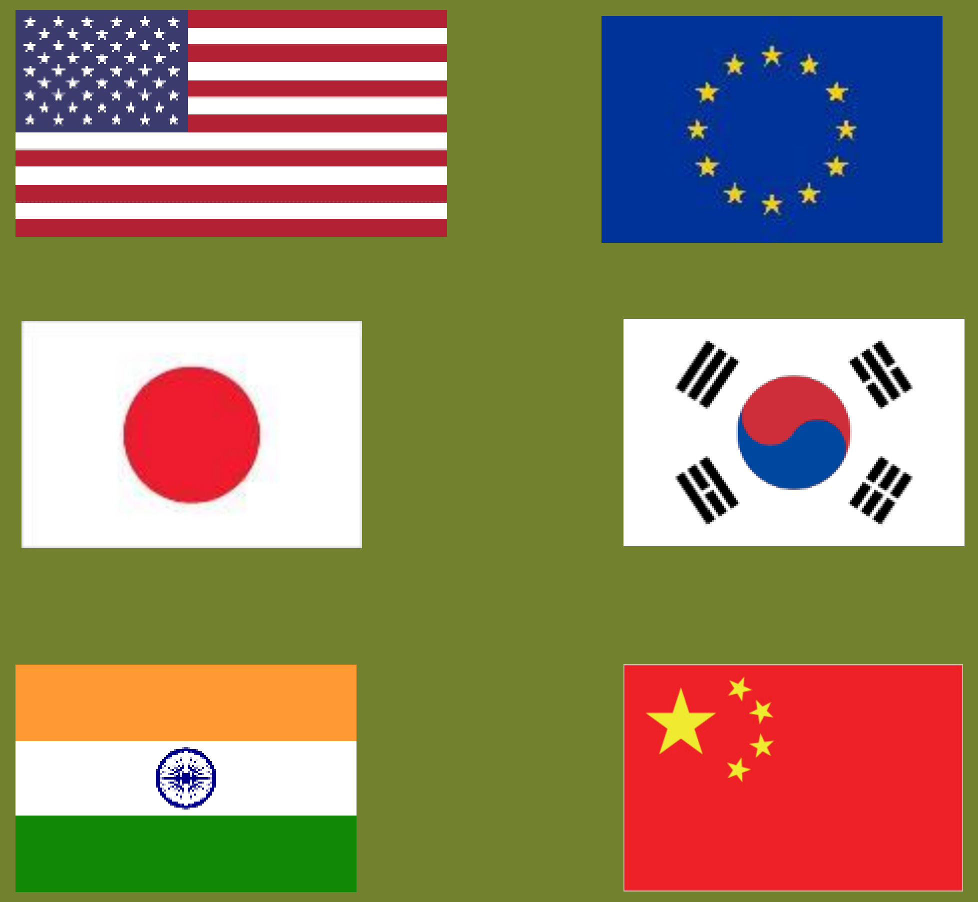
IP has been licensed from the University of Pretoria – exclusive lic.

To licence or not licence? That is the question.

BPF	UK Provisional Patent Application 1720870.3 PCT to be filed
CCII	PCT filed – PCT/IB/2018/058805
All-pass	PCT filed – PCT/IB/2018/058738

- New IP to be developed in the future addressing shortcoming of previous generation implementations
- Freedom to Operate as this will be novel IP

Patent: countries to be filed in, in this order:



TEAM INTRODUCTION

Dr Piotr Osuch
CTO & Co-founder

SAAB GRINTEK DEFENCE
DELPHI
APTIV
MWR INFOSECURITY
SKA AFRICA SQUARE KILOMETRE ARRAY

Nish Singh
COO & Co-founder

imec
5Gphos

Hendrik Nel
RFIC engineer

UPPSALA UNIVERSITET

Dr Tinus Stander
Tech. Advisor

UNIVERSITEIT STELLENBOSCH UNIVERSITY
DENEL
UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA
Denkleiers • Leading Minds • Dikgopolo tša Dihlalefi

Dinesh Maheshwari
Biz. Advisor

Si SILICON CATALYST
CA, USA

- CTO: Memory Division, Cypress Semiconductor
- Board of Directors at JEDEC, UPA; Advisory Board at Kandou Bus, Deca Technologies, Zeno Semiconductor, Tutenna.
- Technologist at Silicon Light Machines, Synopsys, Mentor Graphics, Cadence, Microprocessors & Controls LLC
- ~30 years of Technology, Market and Business strategy in Semiconductors, Systems and Software

STAY CONNECTED

We look forward to forming a partnership

Address

Pretoria, South Africa

Contact Info

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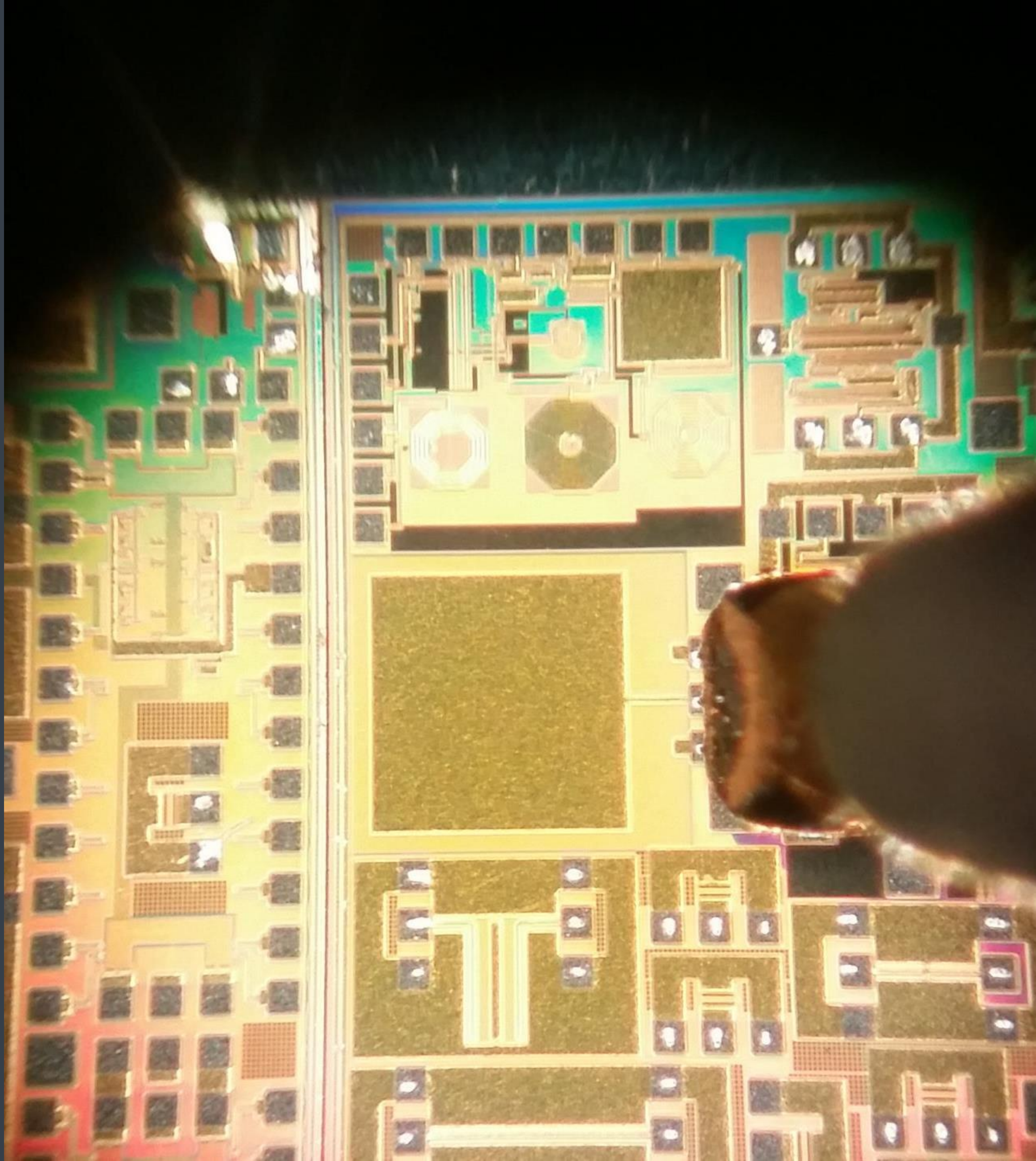
twitter.com/multifractal_sa



APPENDIX – POTENTIAL COMPETITORS

POTENTIAL COMPETITORS (automotive)

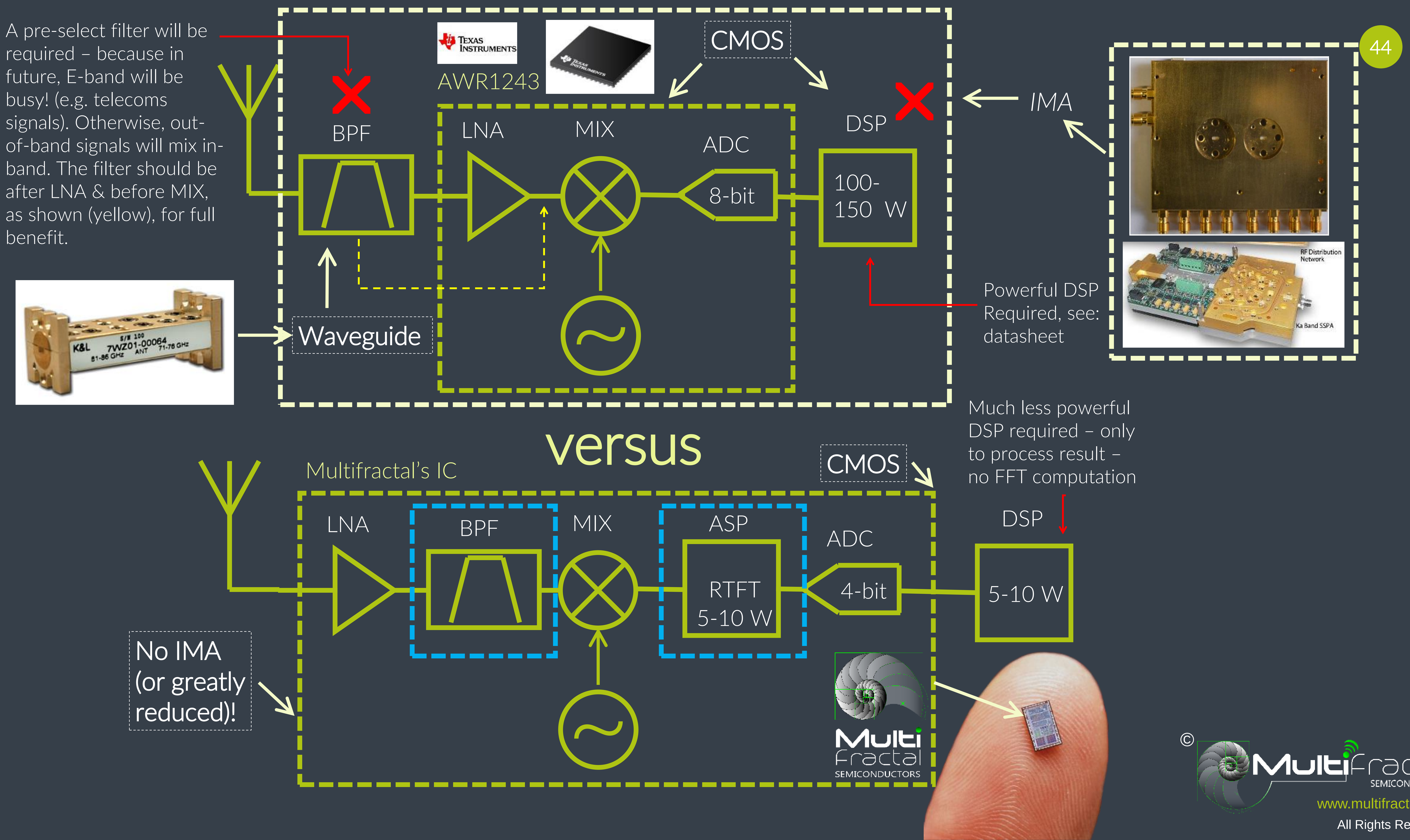
Texas Instruments

AWR1243

- AWR1243 - 76-to-81GHz high-performance automotive MMIC
- RF (chirp) bandwidth = 4 GHz → range resolution ~ 4.5 cm
- Cross-range resolution @ max range ~ 70 cm
- IF bandwidth = 5 MHz → ~1-40 ms per computation cycle (refresh rate)
- Cost: $36 per IC, power: a few W.
- Requirement: powerful DSP for 2D-FFT (range-Doppler): for each TxRx pair! Recommended TI C66x:
  - ~ 20 W per core to do 64 point FFT in 1 µs (1.4 GHz)
  - A few cores will be required:
    - 8 cores: → 140 W – 160 W
    - 16 cores: → 320 W
  - Few thousand $ (ADC+DSP+etc.) ~ $3k

Multifractal's technology will improve on this significantly / add value
∴ TI can be a potential partner or even customer

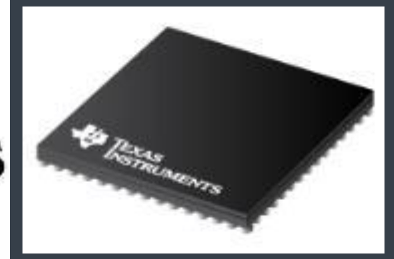
See next slides for details ...


A pre-select filter will be required – because in future, E-band will be busy! (e.g. telecoms signals). Otherwise, out-of-band signals will mix in-band. The filter should be after LNA & before MIX, as shown (yellow), for full benefit.
Texas Instruments
AWR1243
CMOS
BPF
LNA
MIX
ADC
8-bit
DSP
100-150 W
IMA
Waveguide
Powerful DSP Required, see: datasheet
RF Distribution Network
Ka Band SSPA
versus
Multifractal's IC
CMOS
Much less powerful DSP required – only to process result – no FFT computation
LNA
BPF
MIX
ASP
RTFT 5-10 W
ADC
4-bit
DSP
5-10 W
No IMA (or greatly reduced)!
Multi Fractal SEMICONDUCTORS

POTENTIAL COMPETITORS (automotive)

Texas Instruments

AWR1243



Parameter	TI's AWR1243	Multifractal's IC	Our value add
Power consumption	> 100 W (incl. DSP)	< 20 W (incl. DSP)	5-10X reduction
Cost	Thousands $	Hundreds of $	100X reduction
Processing speed	> 1 µs per FFT	< 50 ns per FFT	50X improvement (faster multiple object detection)
IF bandwidth	5 MHz	1-4 GHz	100X faster (faster object detection)
RF bandwidth	4 GHz	4 – 8 GHz	2X larger → 2X resolution (4.5cm → 2.25 cm)
Complexity	Final system design = complex IMA	Final system design = simple/no IMA!	Supports mass production, lower production costs

POTENTIAL COMPETITORS (telecoms)

Tusk IC NV (Antwerp, Belgium)

TUSK IC

- Founded in January 2018 as a spin-off from the KU Leuven ESAT-MICAS research group
- Technology (40 nm CMOS) - link:
  - A Push-Pull Complementary mm-Wave Power Amplifier
  - Waveguide receiver
  - ~0.5 THz signal generators (also in 28nm CMOS)
  - 60 GHz outphasing transmitter (PA with high efficiency)
  - 120 GHz quadrature frequency generator (45 LP CMOS)
  - 118 GHz VCO (65nm CMOS)
  - 200 GHz downconverter (90nm CMOS)

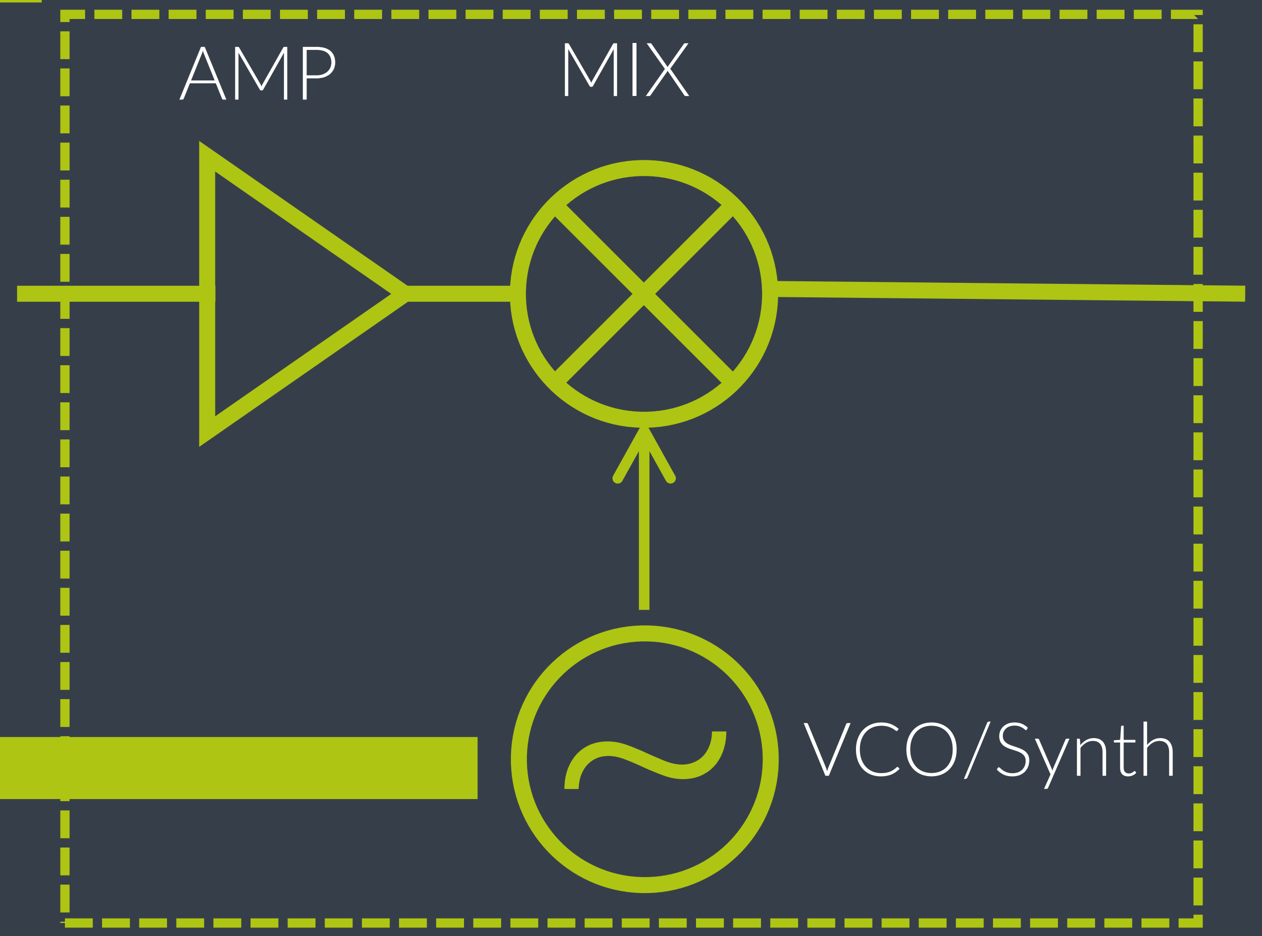
e.g.

Infineon IC: E-band (60-90 GHz)

$63

They have many competitors w.r.t. the AMP and MIX IP

summary



Tusk IC value add is mainly in VCOs and signal generation:

- MACOM VCOs → ~15 GHz
- ANALOG VCOs → ~27 GHz
- Texas Instruments VCOs → ~20 GHz

Not part of Multifractal's value proposition (BPF & ASP)

∴ Tusk IC could be a potential partner or even customer

POTENTIAL COMPETITORS (telecoms)

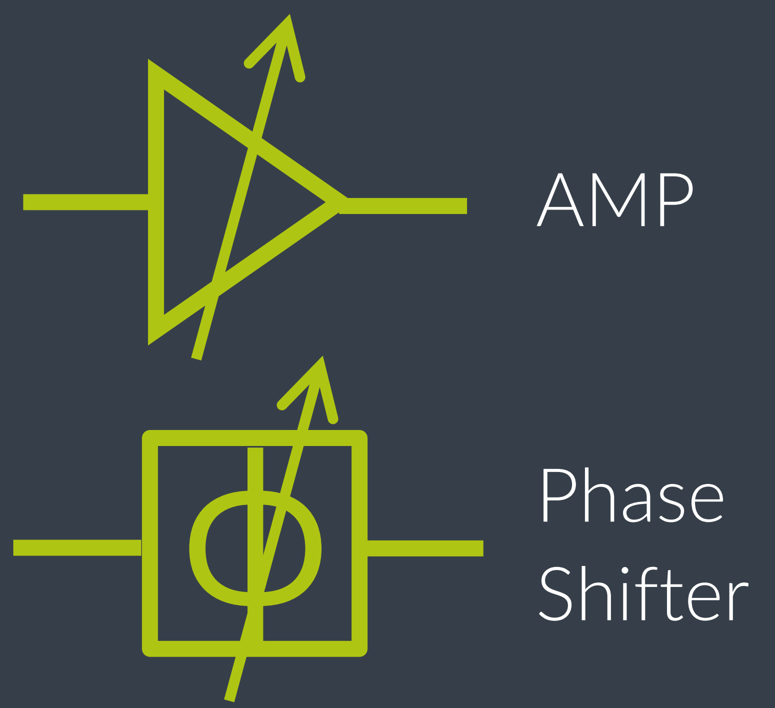
Anokiwave (CA, USA)

- Founded in 1999
- Technology – link:

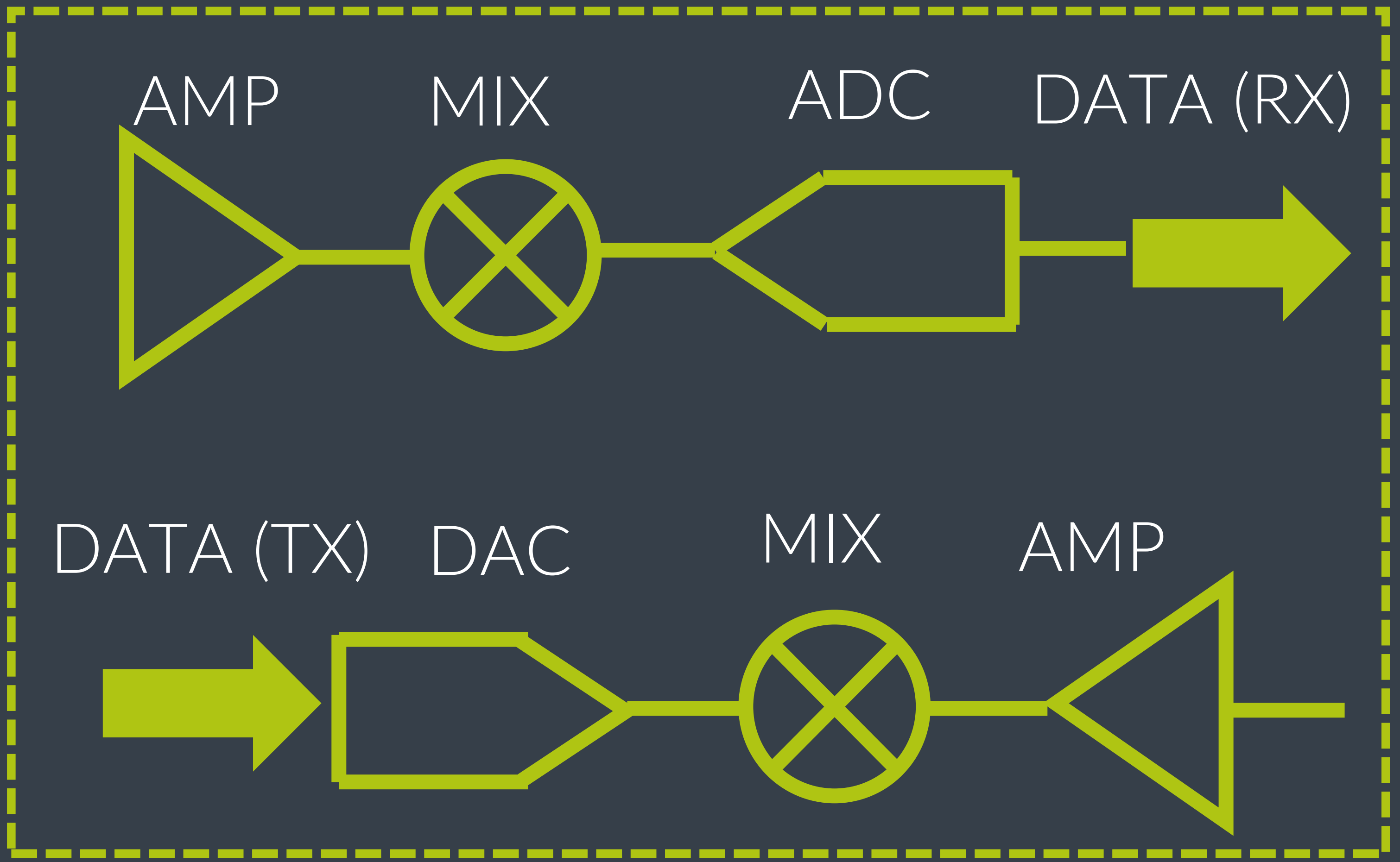
Market	Band	Product Family	Description
5G Communications Active Antennas	24/26 GHz	Silicon Core IC	5G Tx/Rx Quad Core IC
			5G Tx/Rx Quad Core IC
	28 GHz	Silicon Core IC	5G Tx/Rx Quad Core IC
			5G Tx/Rx Quad Core IC
	37/39 GHz	Silicon Core IC	5G Rx Quad Core IC
			5G Tx Quad Core IC
			5G Tx/Rx Quad Core IC
Active Antenna Innovator Kits	24/26 GHz	Active Antenna	256 Element Innovator Kit
	28 GHz	Active Antenna	64 Element Innovator Kit
			256 Element Innovator Kit
RADAR and Communications Active Antennas	X-Band	Silicon Core IC	Dual Beam Low NF Tx/Rx Quad Core IC
			Dual Beam High IIP3 Tx/Rx Quad Core IC
			Single Beam Low NF Tx/Rx Quad Core IC
			Single Beam High IIP3 Tx/Rx Quad Core IC
		RF Front End IC	Medium Power Front End MMIC
SATCOM Active Antennas	K-Band	Silicon Core IC	4-element Dual Pol Rx Quad Core IC
	Ka-Band	Silicon Core IC	4-element Dual Pol Tx Quad Core IC
		PA IC	3W High Power Amplifier MMIC
Multi-Market	Ku-Band	Silicon Core IC	Intelligent Gain Block IC w/ SW
			Intelligent Gain Block IC w/o SW
	Ka-Band	Silicon Core IC	Intelligent Gain Block IC w/ SW
			Intelligent Gain Block IC w/o SW
Point-to-Point Radio Communications	E-Band	LNA IC	Low Noise Amplifier MMIC

summary

Anokiwave's primary value add is in tunable AMPs and Phase Shifters (X, Ku, K, Ka).



At E-band they have a tunable AMP



Not part of Multifractal's value proposition (BPF & ASP)
∴ Anokiwave is most probably a future partner

POTENTIAL COMPETITORS (telecoms)

Other interesting research

- mmWave Circulator IC
  - Columbia Engineering researchers in collaboration with UT-Austin
  - First magnet-free non-reciprocal circulator on a silicon
  - Value proposition: saving real-estate and costs for full–duplex COM Ics
  - Early-stage research (many performance metrics unknown)
  - Existing competitors: none on-chip. There are some products in waveguide such as smiths interconnect.
  - Existing technology uses switches for full-duplex – similar to what they do.
- What does this mean for Multifractal:
  - Not part of our value proposition
  - If they commercialize they could become potential partners
  - … or we could commercialize similar tech before them

APPENDIX – HIGH-LEVEL END-PRODUCT SPECIFICATIONS

LINK BUDGET (telecoms)

Low-level requirements

Center frequency (GHz)	73.50
PA output power (dBm)	20.00
Number of Pas	32.00
Total output power (dBm)	**35.05**
Number of Tx antenna elements	64.00
Tx antenna element gain (dB)	10.00
Antenna & feed network loss (dB)	4.00
Total Tx antenna array gain (dB)	**24.06**
EIRP (dBm)	**59.11**

Distance (m)	300.00
Att no rain (dB/km)	0.50
Att rain 5mm/h (dB/km)	3.00
Att rain 25mm/h (dB/km)	10.00
Att rain 150mm/h (dB/km)	40.00
Att no rain (dB)	0.15
Free space loss	119.31
Path loss (urban)	144.33
Total Path loss (dB) (no rain)	144.48
Total Path loss (dB) (light rain)	145.23
Total Path loss (dB) (heavy rain)	156.33

Received power norm (dBm)	**-85.37**
Received power worst (dBm)	**-97.22**
Bandwidth (MHz)	2000.00
Operating temperature (celsius)	100.00
Thermal noise floor (dBm)	-79.87
Noise Figure (dB)	5.00
SNR (dB) per Rx antenna element	-10.50
Number of Rx antenna element	64.00
Rx antenna element gain (dB)	10.00
Rx antenna feed network loss (dB)	3.50
Total Rx antenna array gain (dB)	**24.56**

SNR after beamforming (norm) (dB)	14.07
SNR after beamforming (worst) (dB)	2.22
Signal power - S (W)	8.30E-10
Signal power worst - S (W)	5.42E-11
Noise power - N (W)	3.26E-12
Eb/no (QPSK) - dB	5.00
BER	5.95E-03
Rb (max bit rate no rain) (gbps)	**161.27**
Rb (max bit rate heavy rain) (gbps)	**10.53**

Technical specification	Multifractal's front-end (gen 1)
Tx power	>35 dBm
Tx antenna array	8x8 or more
EIRP	> 60 dBm
Range	<300 m
Gain	85-100 dB
Channel bandwidth	2 GHz (5 GHz potentially)
Rx elements	8x8 or more
Total Rx antenna gain	>25 dBi
NF	<5 dB
P1dB	> 20 dBm
IP3	> 25 dBm

1 - https://www.itu.int/dms_pub/itu-r/opb/rep/R-REP-M.2376-2015-PDF-E.pdf

2 - http://spathinc.com/spci/downloads/whitepapers/White_Paper_-_A_Straight_Path_Towards_5G.pdf

GENERATION 1 FRONT-END (telecoms)

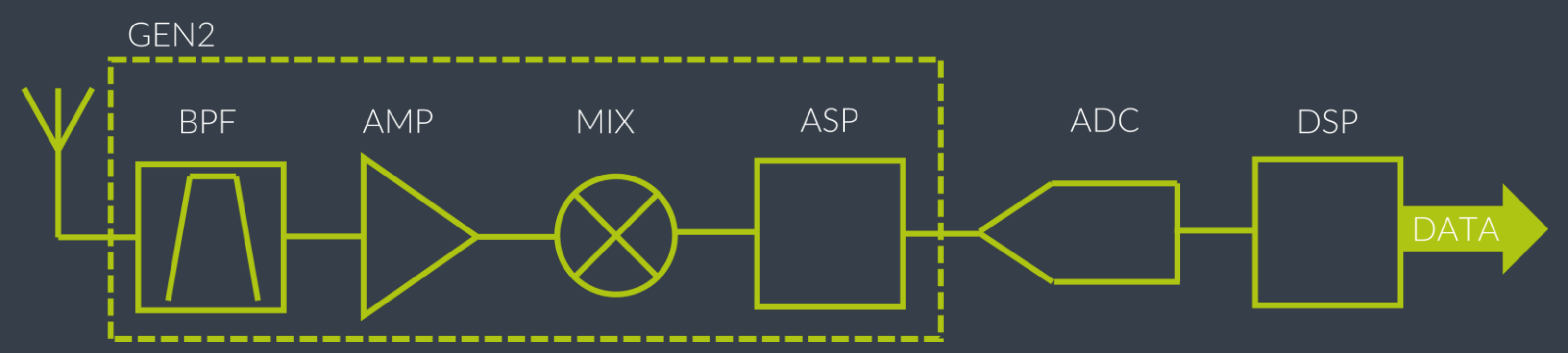
High-level specifications

Parameter	Multifractal's gen 1 front-end	Siklu E-band front-end (EtherHaul 8010FX)	Our value add
Power consumption	< 2 W	50 W (including DSP)	10-20X power reduction
Cost	Tens of $	~$ 11k	>100X cost reduction
Channel bandwidth	5 GHz	2 GHz	SoC solution – fewer components, higher bandwidth, lower power
Throughput	10 Gbps full duplex	10 Gbps full duplex (FDD)	-
RF bands	71-76, 81-86 GHz	71-76, 81-86 GHz	-
System gain	80 – 98 dB	64 – 93 dB	-
Range	300 m	2.73 – 3.7 km	Small cell densification
Operating temperature	-45 to +85°C ++	-45 to +55°C	Single chip solution – better temperature performance / match
Dimensions	~ 10 by 10 cm (with MIMO array) – RF module (~5x5 cm)	~ 30 by 30 cm (single antenna – no MIMO)	Massive MIMO
Weight	< 100 g	~ 5 kg	Small, lightweight
NF	~5 dB	?	Relxed requirements due to small cell dens.

Smaller range has benefits – our solution allows for this small cell dens. due to lower costs, power and size

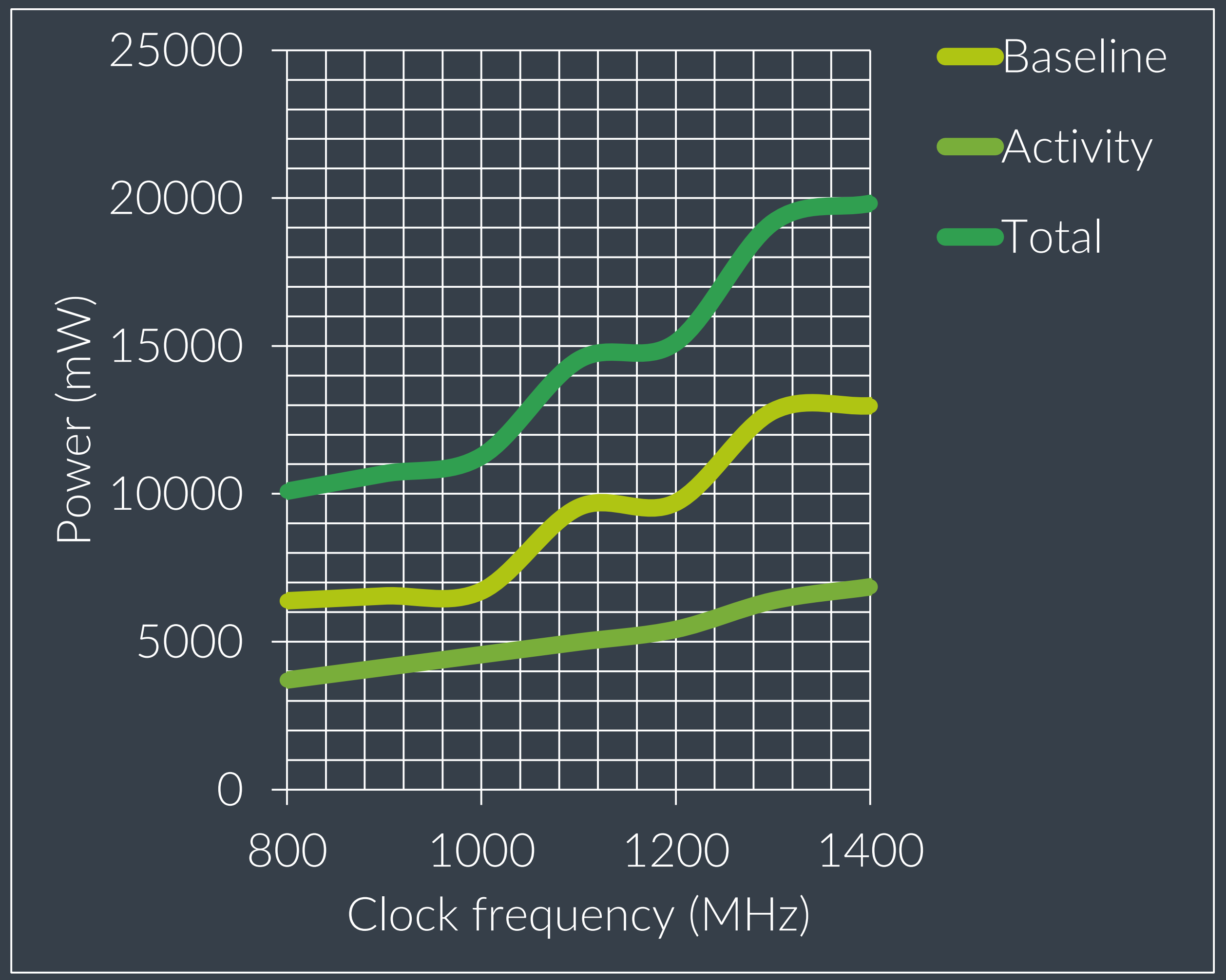
GENERATION 2 FRONT-END (telecoms)

High-level specifications (ASP only – cognitive radio – other specs stay the same)



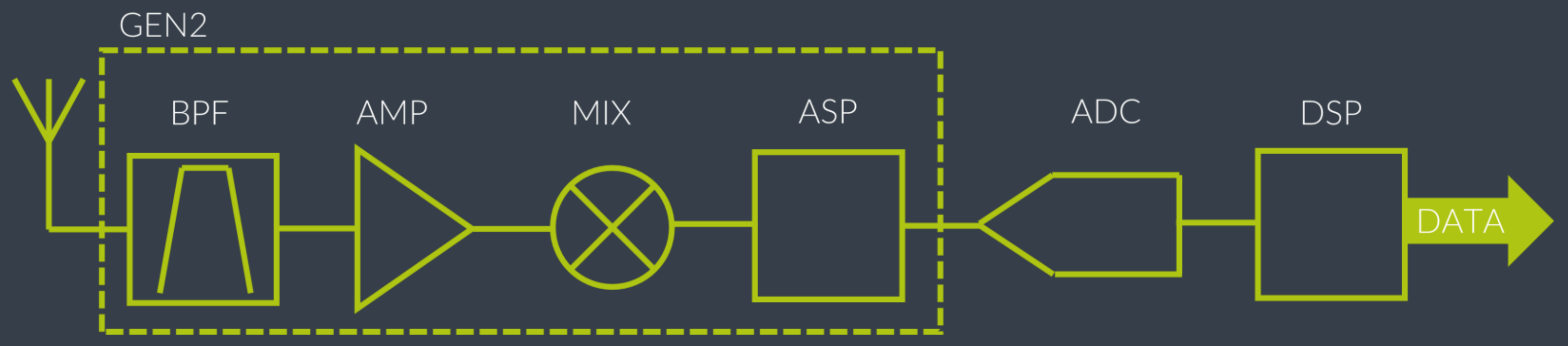
Existing solution do not scale well with bandwidth

TI 66x (8 cores)



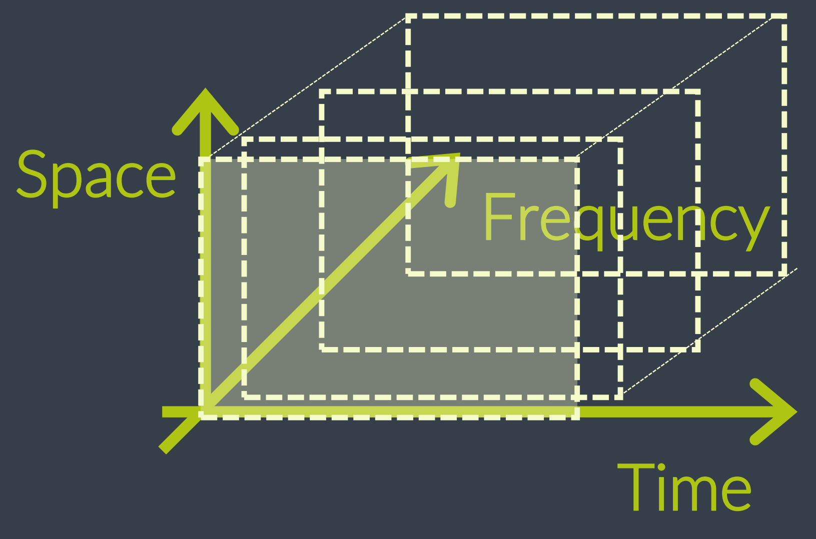
Parameter	Multifractal's IC	TI's AWR1243 / DSP 66x series or equivalent	Our value add
Power consumption	< 20 W (incl. DSP)	> 100 W (incl. DSP)	5-10X reduction
Cost	Hundreds of $	Thousands $	>100X reduction
Processing speed	< 50 ns per FFT	> 1 µs per FFT (1 core)	50X improvement (faster multiple object detection)
IF bandwidth (automotive radar)	1-4 GHz	5 MHz	100X faster (faster detection)
RF bandwidth (automotive radar)	4 – 8 GHz	4 GHz	2X larger → 2X resolution (4.5cm → 2.25 cm)
Complexity	Final system design = simple/no IMA!	Final system design = complex IMA	Supports mass production, lower production costs
Dynamic range	50 dB	~50 dB	-
ENOB	4	8	Relaxed ADC requirements
Equivalent n-points	70 (current technology with the aim to improve)	-	-
Power accuracy	±3 dB	~ 1 dB	-
Frequency accuracy	~ 100 Mhz	~ 100 MHz	-
Magnitude / phase information	Magnitude only	Both	Application dependent

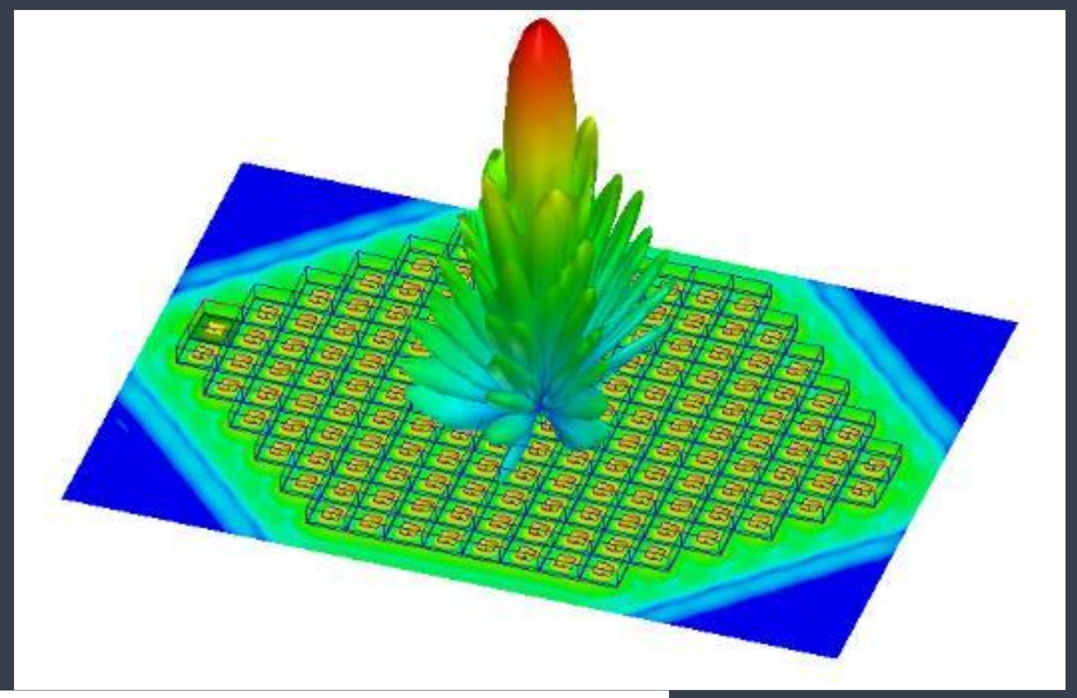
GENERATION 2 FRONT-END (telecoms)

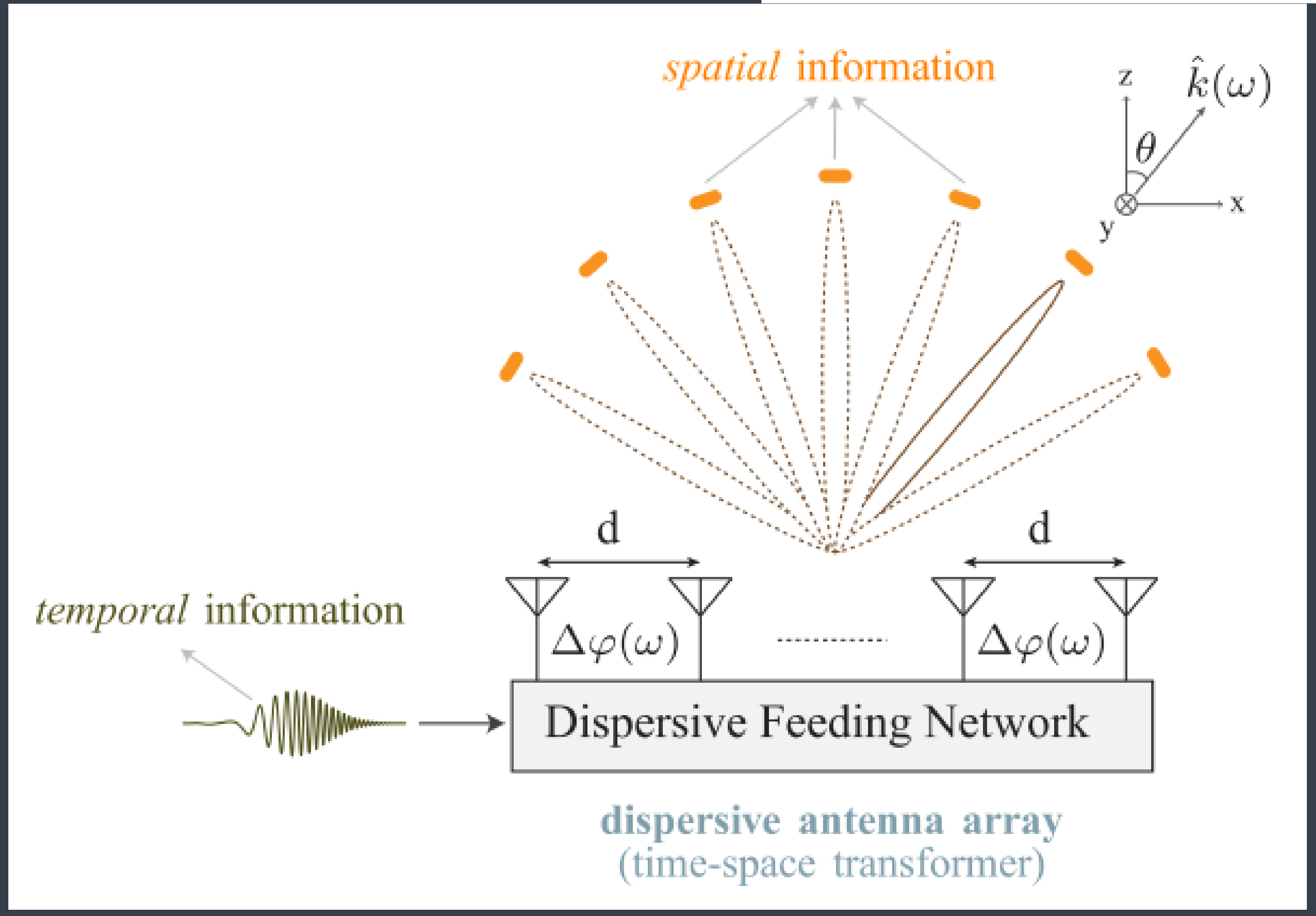


High-level specifications (ASP only – frequency beam steering – other specs stay the same)

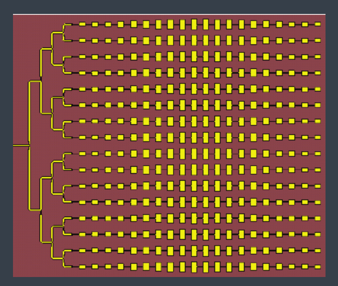
Parameter	Multifractal's IC	TI's AWR1243 / DSP 66x series or equivalent	Our value add
Power consumption	< 20 W (incl. DSP)	> 100 W (incl. DSP)	5-10X reduction
Cost	Hundreds of $	Thousands $	10X reduction
Processing speed (tracking speed)	< 50 ns per operation	> 1 µs per operation (1 core)	50X improvement (faster steering)
Complexity	Final system design = simple/no IMA!	Final system design = complex IMA	Supports mass production, lower production costs
Dynamic range	50 dB	~50 dB	-
Bandwidth	> 8GHz	4 GHz is already a challenge	
Channels per antenna (frequency mapped to angles)	> 30 (only one array! – one tile)	? (Unheard of) – many tiles / antenna arrays needed	More massive MIMO! Truly big data.
Frequency reconfigurability (lens effect)	8 GHz band → 100 MHz band	Unheard of	Frequency lensing



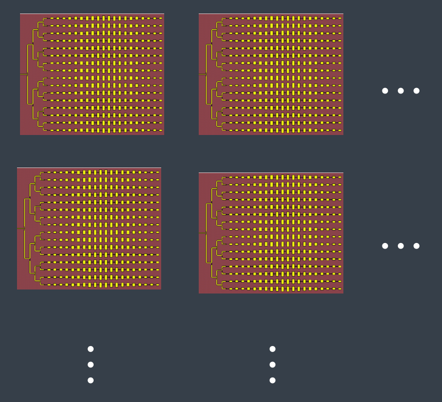




One array



vs



Many arrays

APPENDIX - TECHNOLOGY OVERVIEW

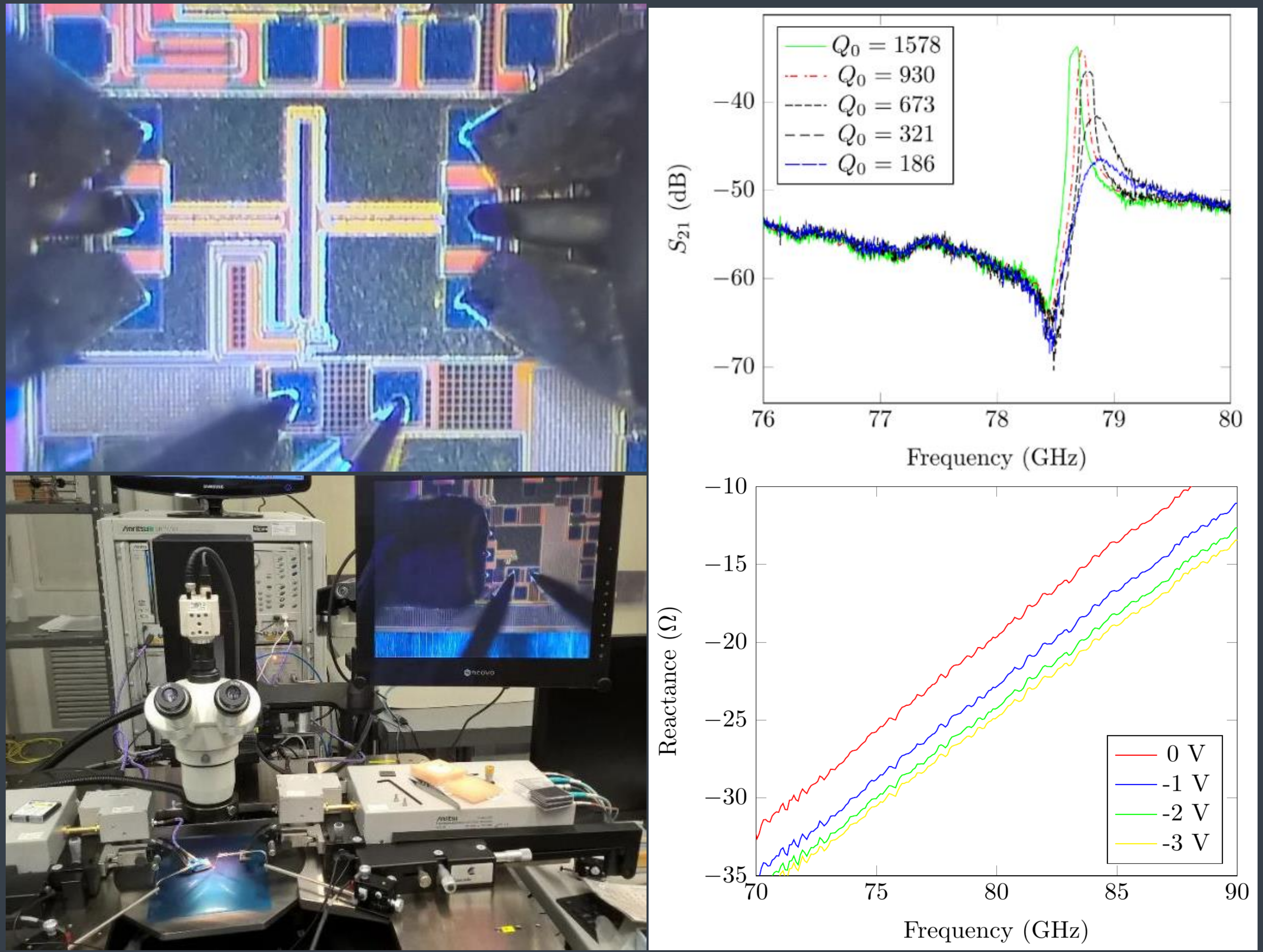
TECHNOLOGY OVERVIEW

UK Provisional Patent Application 1720870.3
PCT to be filed in next few weeks

1. Fully tunable, active, enhanced, high Q-factor mm-wave resonators

Manufactured using: GLOBAL FOUNDRIES

- Resonator is the building block of the BPF. Nobody in industry has integrated BPF on Silicon due to low Q_0-factors.
- Silicon-proven in 130nm BiCMOS GF US 8HP with HBT fT/fMAX 260/320 GHz
- SOTA Q_0 of ≈10, Our Q_0 of ≈1000
- Can be scaled for other mmWave frequencies and processes (XXnm, CMOS, SOI, BiCMOS)
- E-band (71-76 and 81-86 GHz)
- Centre frequency and Q-factor tunable post-production with control voltages



First-ever on-chip mm-wave microstrip resonators with Q > 100

TECHNOLOGY OVERVIEW

UK Provisional Patent Application 1720870.3
PCT to be filed in next few weeks

1. Fully tunable, active, enhanced, high Q-factor mm-wave resonators

Manufactured using: GLOBAL FOUNDRIES

f_0 (GHz)	FBW	Process	IL (dB)	Q-factor	Ref.
78	< 10 %	0.13 µm SiGe BiCMOS	< 0.1	> 1500	This work
77	15.5 %	0.14 µm SiGe BiCMOS	6.4		[1]
77	11.7 %	0.13 µm standard CMOS	3.9		[2]
77	28.6 %	0.18 µm standard CMOS	3.8		[3]
70	25.7 %	0.18 µm standard CMOS	3.6		[4]
65.0	3.23%	0.15 µm GaAs	2.8	< 100	[6]
65.0	4.00%	0.15 µm GaAs	3.0		[6]
22.7	7.39%	0.18 µm CMOS	0.15		[7]
6.45	17.05%	2.00 µm GaAs	0.25 gain		[8]

1. B. Dehlink, M. Engl, K. Aufinger, and H. Knapp, "Integrated Bandpass Filter at 77 GHz in SiGe Technology," IEEE Microw. Wirel. Components Lett., vol. 17, no. 5, pp. 346–348, May 2007.
2. Y.-M. Chen and S.-F. Chang, "A ultra-compact 77-GHz CMOS bandpass filter using grounded pedestal stepped-impedance stubs," 41st Eur. Microw. Conf., no. October, pp. 194–197, 2011.
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TECHNOLOGY OVERVIEW

PCT filed – PCT/IB/2018/058738

2. Tunable active second-order all-pass network (CMOS)

Manufactured using:

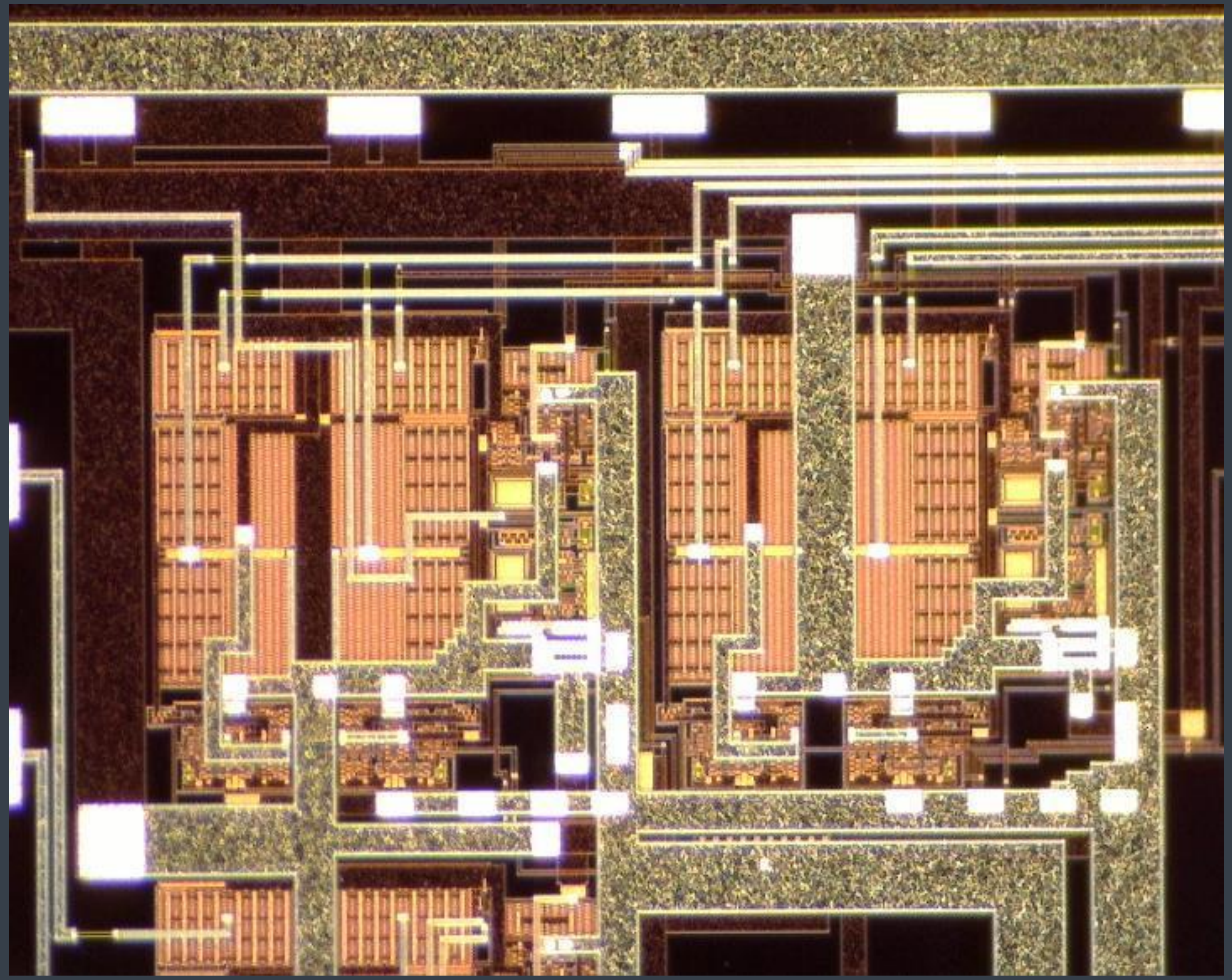
Second-order all-pass network - building block of any ASP

SOTA all-pass network - bulky soft-substrate passive microstrip

Multifractal - first-ever active on-chip second-order all-pass network with delay Q-value larger than 1

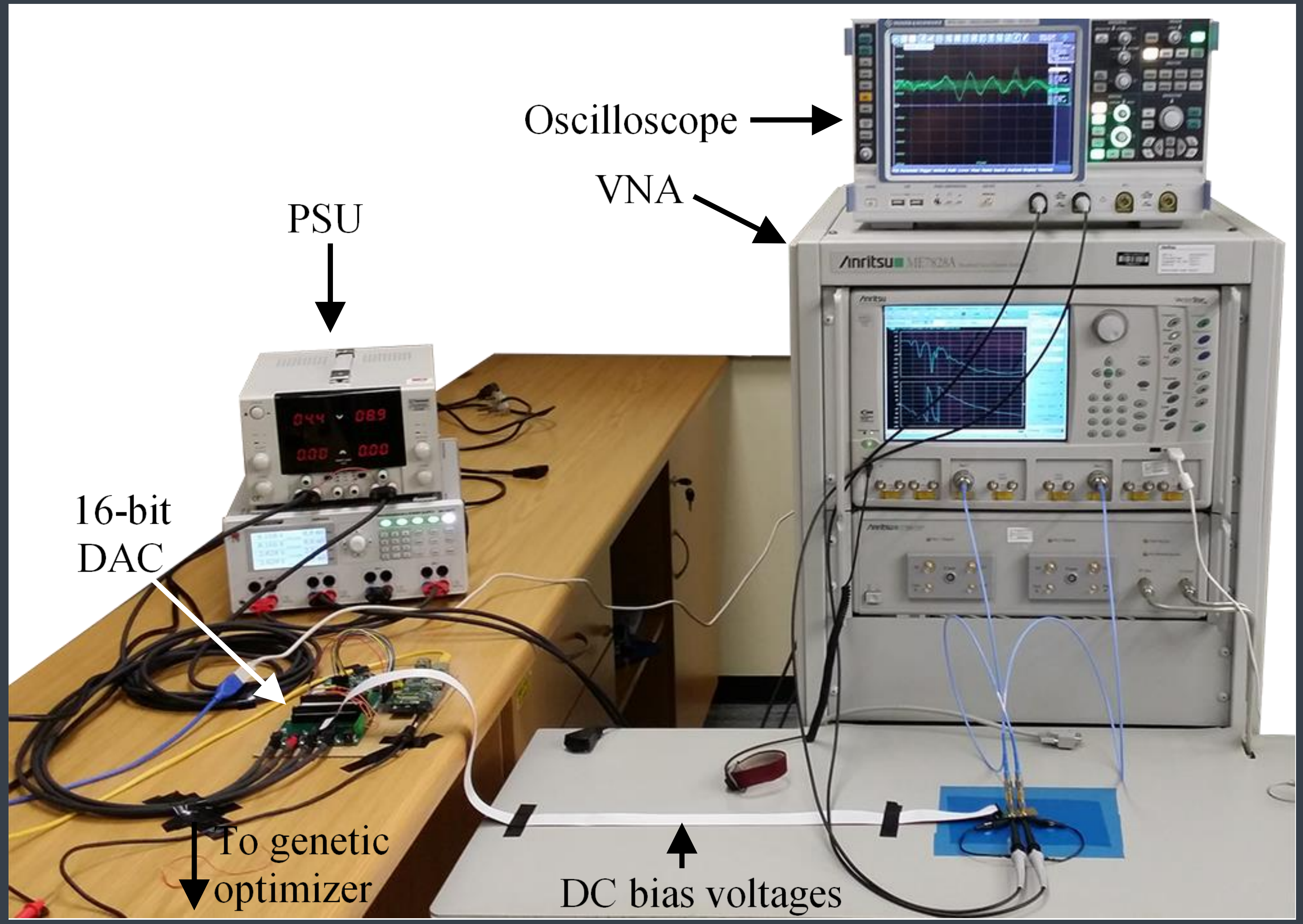
- Low insertion loss ripple (< 3.1 dB)
- Bandwidth of 280 MHz in 0.35 um CMOS
- 0.0625 mm^2 real-estate
- Reduced sensitivity to process tolerances

Prototyped in 0.35 um CMOS and measured



Second-order all-pass network – micrograph

100 microns



Second-order all-pass network – measurement setup

TECHNOLOGY OVERVIEW

PCT filed – PCT/IB/2018/058738

2. Tunable active second-order all-pass network (CMOS)

Ref.	ORDER	Q_D	f_0 (GHz)	-3dB Bandwidth (GHz)	Technology	# of L	Size (mm^2)	Power (mW)	Magnitude variation (dB)
This work	2nd	1.15	0.073	0.280	0.35 µm CMOS	0	0.0625	15 (excl. DAC)	3.1
[1]	2nd	0.19 (0.59)***	3	4	0.25 µm CMOS	0	0.085	< 95	1.5 (> 25)
[2]	2nd	0.04 (0.52)	7	13	0.13 µm CMOS	1	0.0627	18.5	0.5 (> 13)
[3]	2nd	0.098	7	16.5	0.09 µm CMOS	0	-	< 27	< 1
[4]	2nd	0.049 (0.61)	6.3	12	0.13 µm CMOS	1	-	16.5	~ 1.5 (> 10)
[5]	2nd	0.047	6	7.5	SiGe BiCMOS HBT (f_T = 95 GHz)	1	0.49*	121	~ 1
[6]	2nd (f_0 = 0)**	0	0	12.2	0.16 µm CMOS	0	0.15	90	1.4
[7]	0th (f_0 = 0)**	0	0	10	SiGeRF HBT (f_T = 80 GHz)	2	0.4197	38.8	2 – 2.5
[8]	2nd (f_0 = 0)**	0	0	4.38	0.18 µm CMOS	0	0.0512	7.88	-
[9]	2nd (f_0 = 0)**	0	0	> 3	0.13 µm CMOS	0	0.29	112	~ 0.75

* Including pads, ** constant delay with frequency, *** values in brackets are computed over the entire bandwidth with the associated magnitude variation also shown in brackets.

1. Lin, X., Liu, J., Lee, H., Liu, H.: 'A 2.5- to 3.5-Gb/s adaptive FIR equalizer with continuous-time wide-bandwidth delay line in 0.25-µm CMOS'IEEE Journal of Solid-State Circuits, 2006, 41, (8), pp. 1908–1918.
2. Ahmadi, P., Maundy, B., Elwakil, A.S., Belostotski, L., Madanayake, A.: 'A new second-order all-pass filter in 130-nm CMOS'IEEE Transactions on Circuits and Systems II: Express Briefs, 2016, 63, (3), pp. 249–253.
3. Maeng, M., Bien, F., Hur, Y., et al.: '0.18-um CMOS equalization techniques for 10-Gb/s fiber optical communication links'IEEE Transactions on Microwave Theory and Techniques, 2005, 53, (11), pp. 3509–3519.
4. Ahmadi, P., Taghavi, M.H., Belostotski, L., Madanayake, A.: '10–GHz current-mode 1st and 2nd order allpass filters on 130nm CMOS', in 'IEEE 56th International Midwest Symposium on Circuits and Systems' (2013), pp. 1–4
5. Hamouda, M., Fischer, G., Weigel, R., Ussmueller, T.: 'A compact analog active time delay line using SiGe BiCMOS technology', in '2013 IEEE International Symposium on Circuits and Systems' (2013), pp. 1055–1058
6. Garakoui, S.K., Klumperink, E.A., Nauta, B., van Vliet, F.E.: 'Compact cascadable gm-C all-pass true time delay cell with reduced delay variation over frequency'IEEE Journal of Solid-State Circuits, 2015, 50, (3), pp. 693–703.
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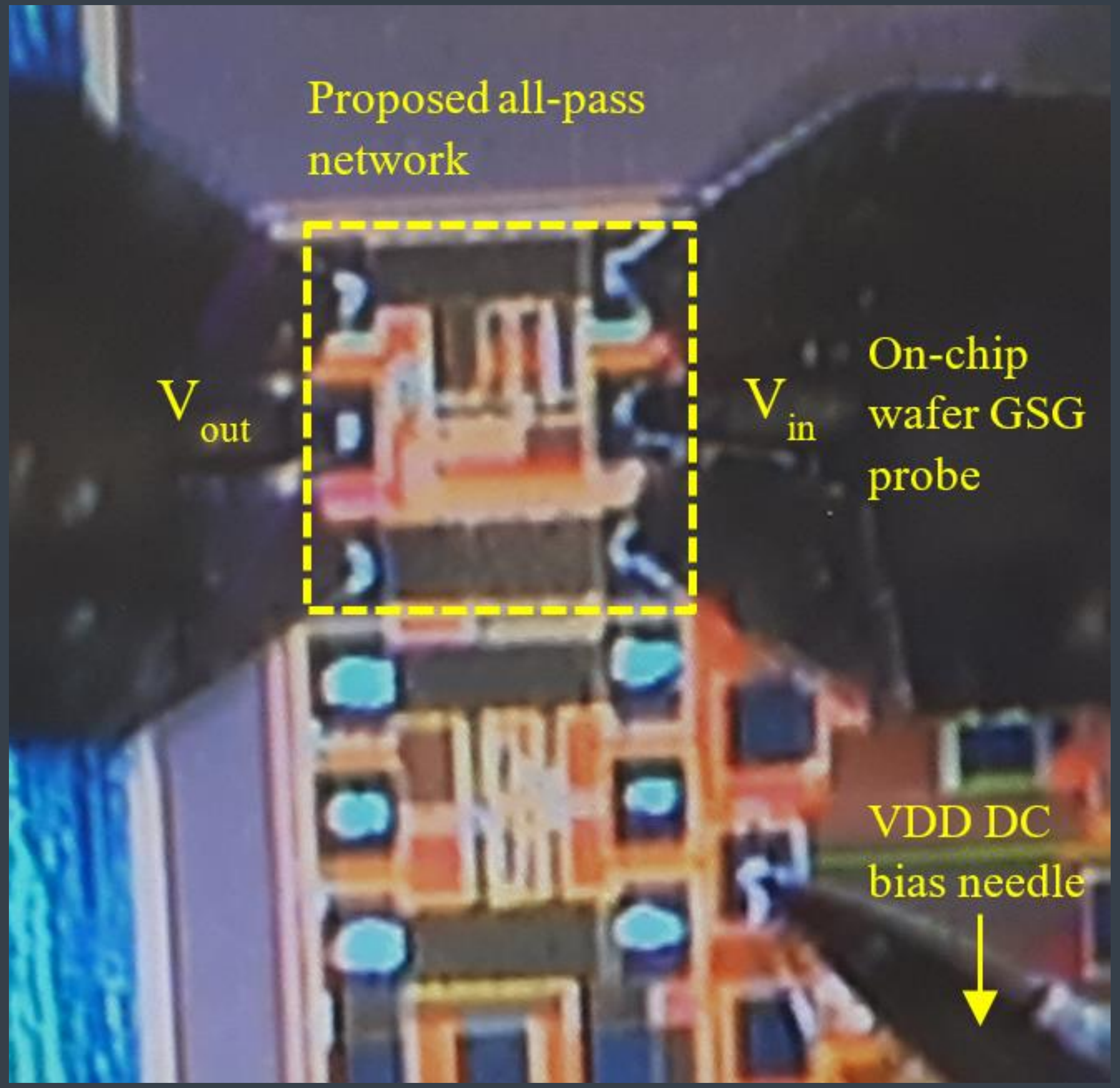
TECHNOLOGY OVERVIEW

Know-how

3. Mm-wave active second-order all-pass network (BiCMOS)

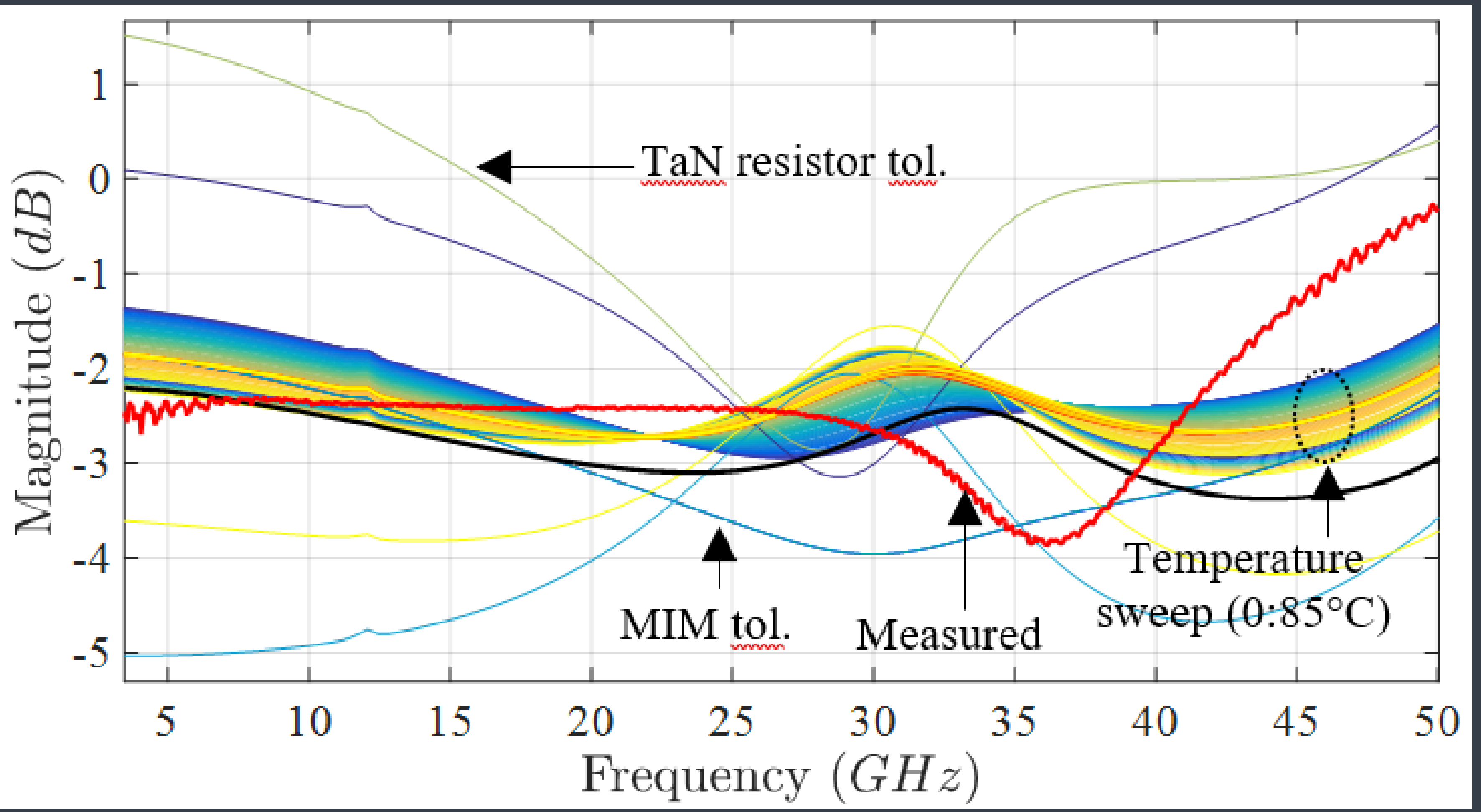
- First mm-wave second-order all-pass network: 10 GHz linear group delay bandwidth
- Prototype - 130 nm BiCMOS
- Power – 20 mW
  Size - 0.09 mm^2
- Average output noise of 0.69 nV/√Hz
- Prototyped, measurements pending

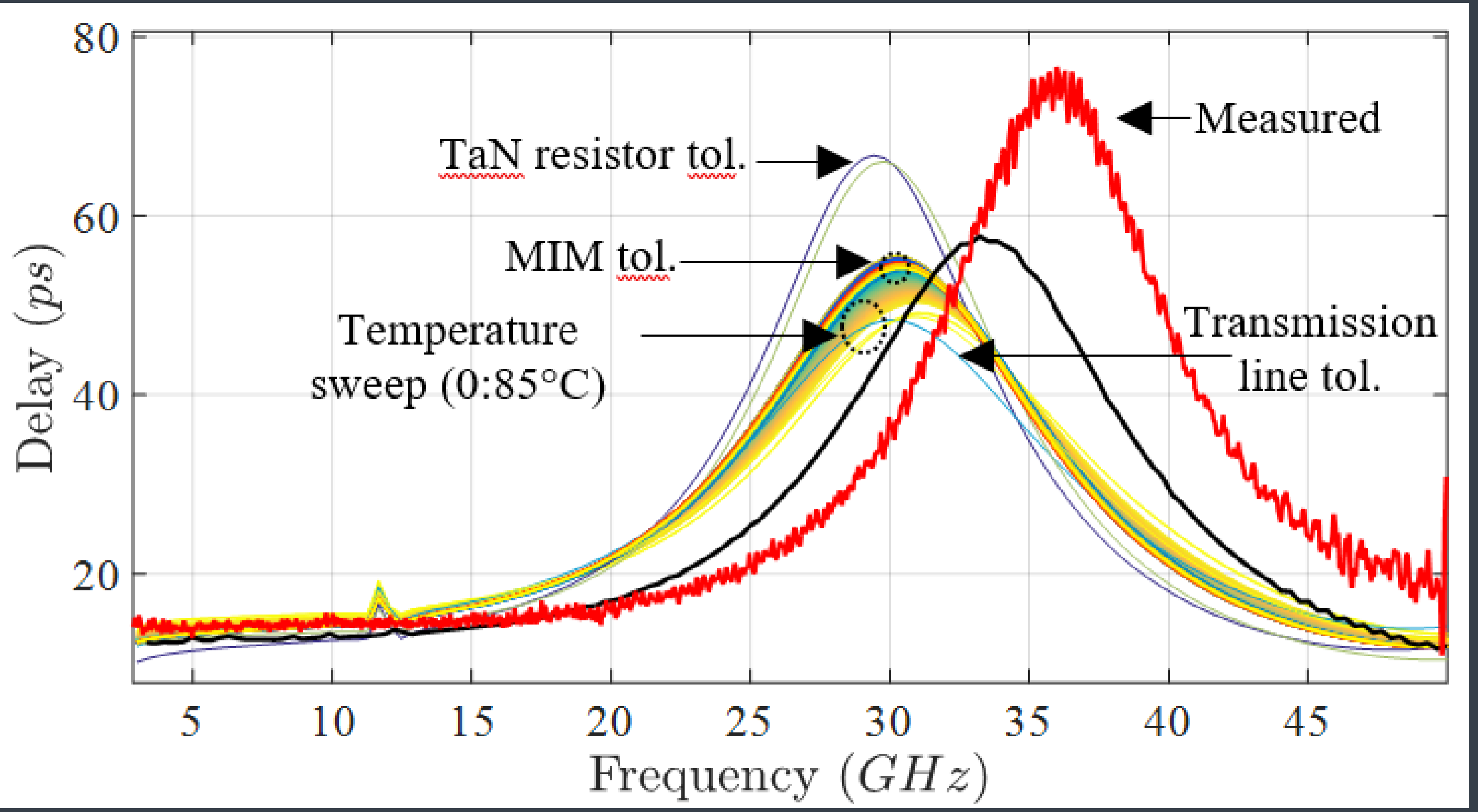
Manufactured using: GLOBALFOUNDRIES



Mm-wave bandwidth CCII – micrograph

150 microns





Mm-wave bandwidth CCII – simulated results

TECHNOLOGY OVERVIEW

Know-how

3. Mm-wave active second-order all-pass network (BiCMOS)

	Q_D	f_0 (GHz)	-3dB (GHz)	Technology	Size (mm^2)	Power (mW)	$\Delta \lvert T \rvert$ (dB)**
[*]	3.6	36	40	0.13 µm SiGe	0.0625	9.3	1.4
[4]	0^	0	12.2	0.16 µm CMOS	0.07	90	~ 1.4
[5]	0^	0	4.38	0.18 µm CMOS	0.0512	7.88	-
[7]	0.19	3	4	0.25 µm CMOS	0.085	< 95	~ 1.5
[8]	0.04	7	13	0.13 µm CMOS	0.0627	18.5	~ 0.5
[9]	0.098	7	16.5	0.09 µm CMOS	-	< 27	< 1
[10]	0.049	6.3	12	0.13 µm CMOS	-	16.5	~ 1.5
[11]	0.047	6	7.5	0.25 µm SiGe	0.49#	121	~ 1

*This work. ^Cascaded two first-order sections (no complex pole/zero). #Including pads. **T represents either a power or voltage transfer function.

1. S. K. Garakoui, E. A. Klumperink, B. Nauta, and F. E. van Vliet, "Compact cascadable gm-C all-pass true time delay cell with reduced delay variation over frequency," IEEE Journal of Solid-State Circuits, vol. 50, no. 3, pp. 693–703, 2015.
2. Y. W. Chang, T. C. Yan, and C. N. Kuo, "Wideband time-delay circuit," in European Conference In Microwave Integrated Circuits, 2011, pp. 454–457.
3. X. Lin, J. Liu, H. Lee, and H. Liu, "A 2.5- to 3.5-Gb/s adaptive FIR equalizer with continuous-time wide-bandwidth delay line in 0.25-µm CMOS," IEEE Journal of Solid-State Circuits, vol. 41, no. 8, pp. 1908–1918, 2006.
4. P. Ahmadi, B. Maundy, A. S. Elwakil, L. Belostotski, and A. Madanayake, "A new second-order all-pass filter in 130-nm CMOS," IEEE Transactions on Circuits and Systems II: Express Briefs, vol. 63, no. 3, pp. 249–253, 2016.
5. M. Maeng et al., "0.18-um CMOS equalization techniques for 10-Gb/s fiber optical communication links," IEEE Transactions on Microwave Theory and Techniques, vol. 53, no. 11, pp. 3509–3519, 2005.
6. P. Ahmadi, M. H. Taghavi, L. Belostotski, and A. Madanayake, "10–GHz current-mode 1st and 2nd order allpass filters on 130nm CMOS," in IEEE 56th International Midwest Symposium on Circuits and Systems, 2013, pp. 1–4.
7. M. Hamouda, G. Fischer, R. Weigel, and T. Ussmueller, "A compact analog active time delay line using SiGe BiCMOS technology," in 2013 IEEE International Symposium on Circuits and Systems, 2013, pp. 1055–1058.

TECHNOLOGY OVERVIEW

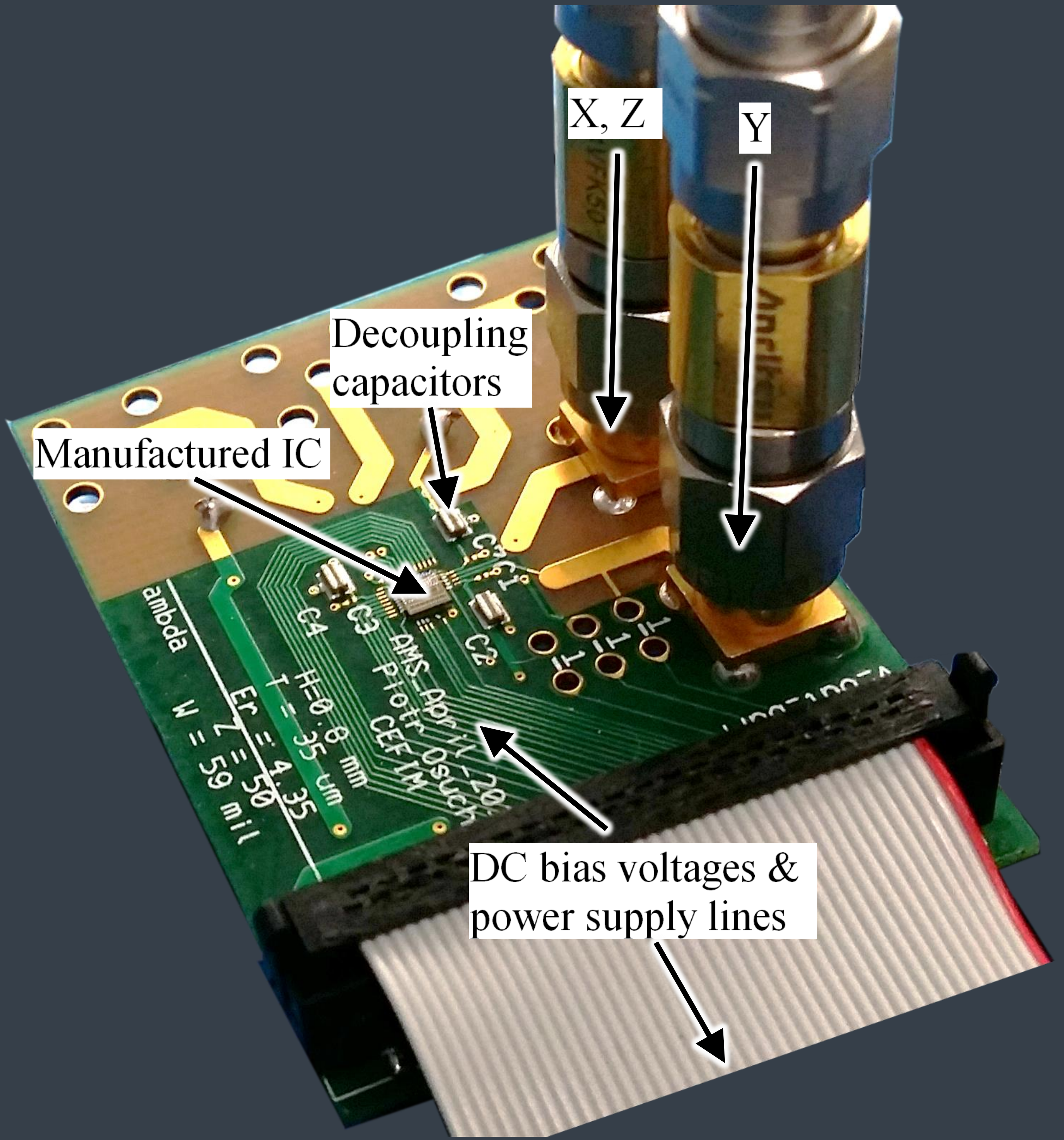
PCT filed – PCT/IB/2018/058805

Manufactured using:

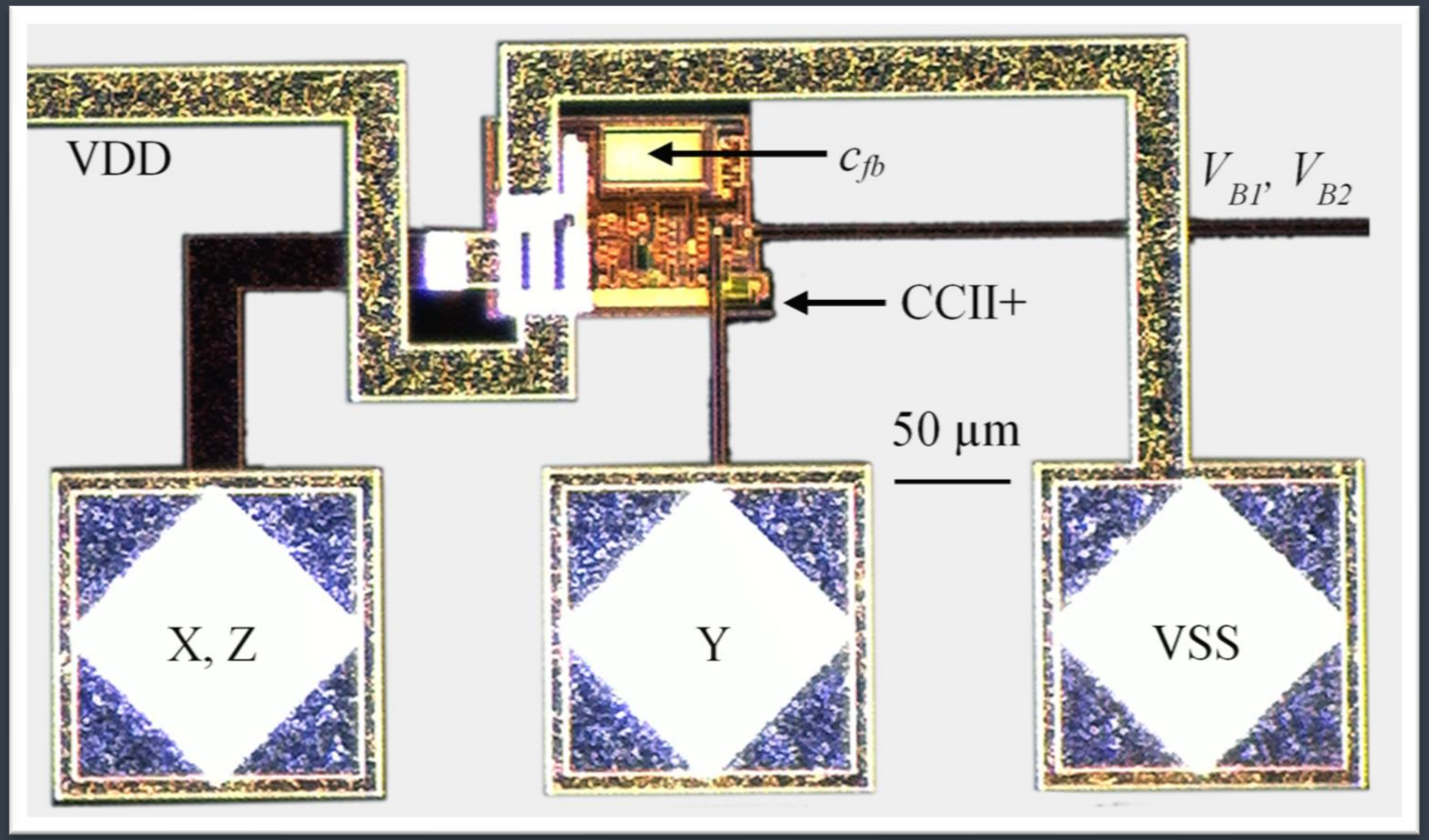
ams

4. High-precision CMOS CCII with stability and peaking control

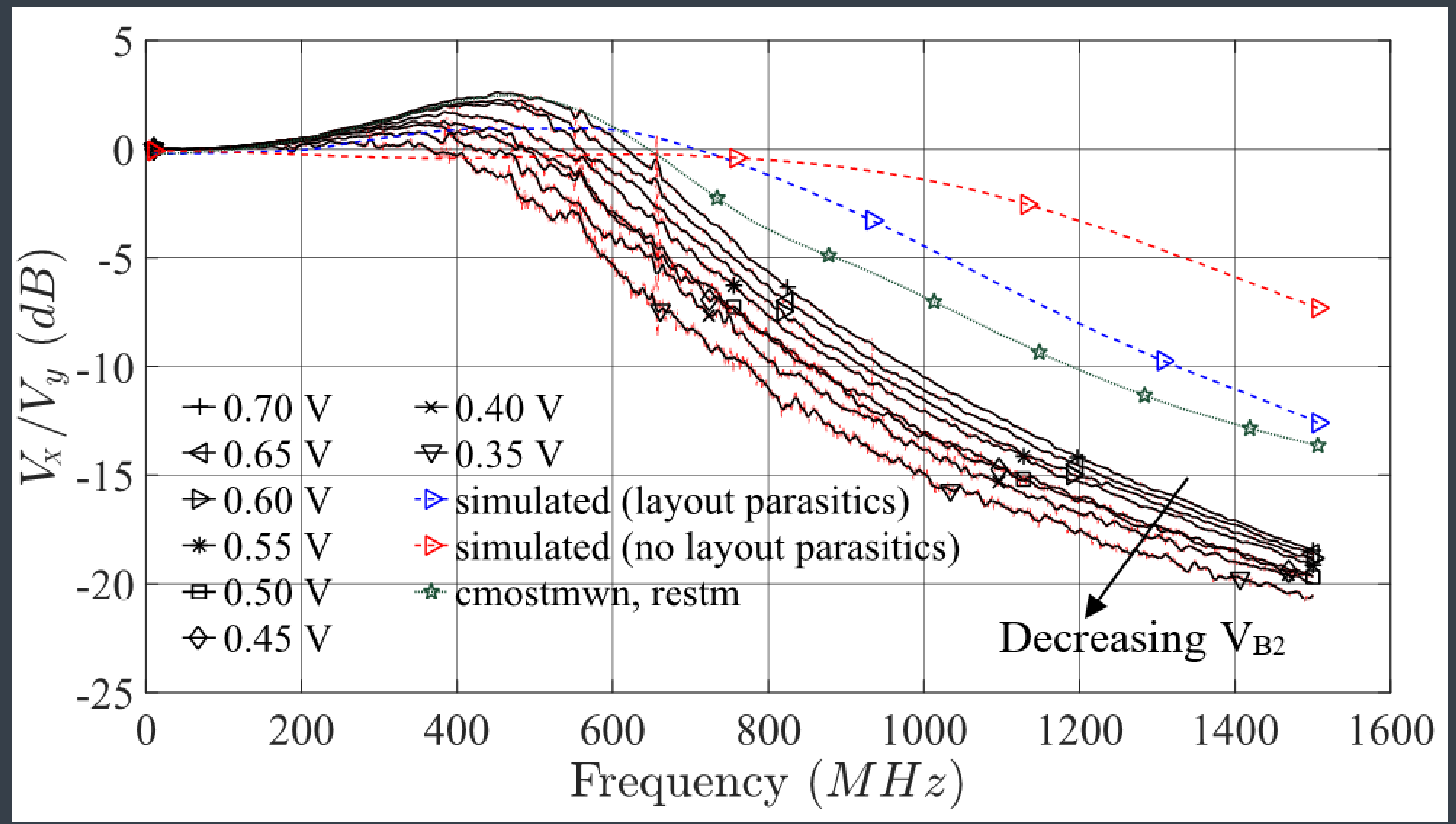
- A CCII is a versatile analogue building block (of for e.g. all-pass networks)
- Large bandwidths (800 MHz – 350 nm CMOS)
- High accuracy (feedback mechanism) - voltage and current following to within 0.5 %
- Stability of the feedback loop (post-production tunable phase margin)
- Post-production peaking control (reduce ripple) to account for process tolerances
- Prototyped and measured:
  Power – 5 mW
  Size – 0.023 mm2



CCII+ – measurement setup



CCII+ – micrograph



CCII+ – measurement

TECHNOLOGY OVERVIEW

PCT filed – PCT/IB/2018/058805

Manufactured using: ams

4. High-precision CMOS CCII with stability and peaking control

Ref.	Voltage gain (β)	Current gain (α)	R_X (Ω)	R_Y (kΩ)	R_Z (kΩ)	-3dB Bandwidth (MHz)	Technology	Measured Results
This work	1.0115	1.0115	< 5	45	20	500	0.35 µm CMOS	Yes
[1]	-	-	100	-	-	~1	off-chip	Yes
[2]	0.9886	-	0.3	-	-	20	1.2 µm CMOS	No
[3]	0.99	0.99	2.3	-	-	10	0.6 µm CMOS	No
[4]	1	1	11.4	-	7200	16	0.35 µm CMOS	No
[5]	-	-	~50	-	-	700	1.2 µm CMOS	No
[6]	0.9999	0.9999	0.06	-	-	2.16	0.5 µm CMOS	No
[7]	0.96	0.976	18	25	35	2600	0.35 µm CMOS	No
[8]	0.995	-	1.15	3900	2800	~50	0.35 µm CMOS	No
[9]	1.0000	0.9999	3.7	-	-	~400	0.5 µm CMOS	No
[10]	1.0005	1.0015	0.003	-	-	~250	1.2 µm CMOS	No

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10. A. Awad and A. M. Soliman, "New CMOS realization of the CCII-," IEEE Transactions on Circuits and Systems II: Analog and Digital Signal Processing, vol. 46, no. 4, pp. 460–463, 1999.

TECHNOLOGY OVERVIEW

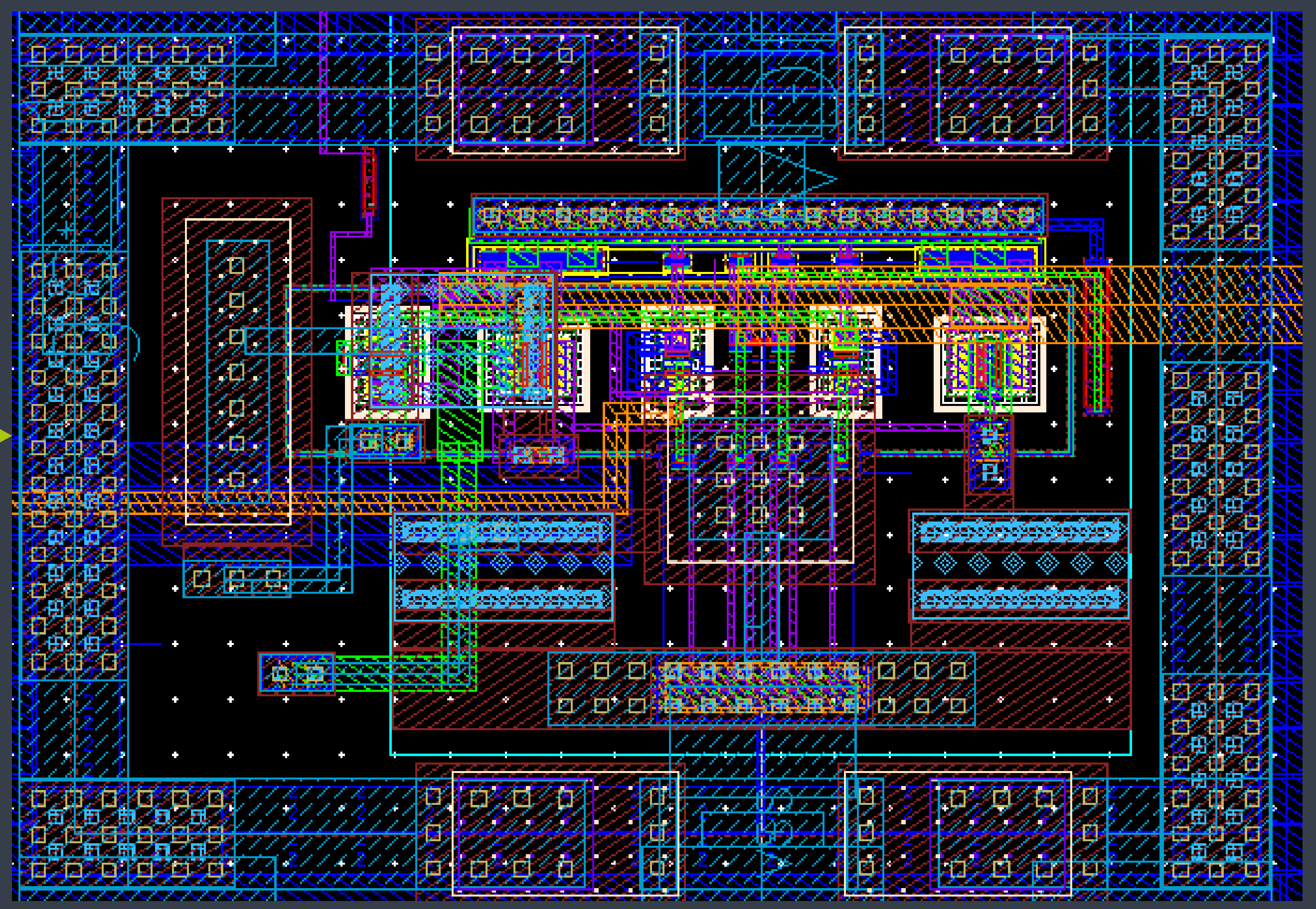
Know-how, PCT to be filed (potentially)

5. Mm-wave bandwidth CCII with peaking reduction (BiCMOS)

Manufactured using: GLOBAL FOUNDRIES

- Mm-wave bandwidths (27 GHz) - first time ever.
- Feedback mechanism to improve precision (to within 1 %)
- Peaking reduction (reduce passband ripple)
- Prototyped and measured - post-processing pending

First-ever mm-wave bandwidth CCII



150 microns

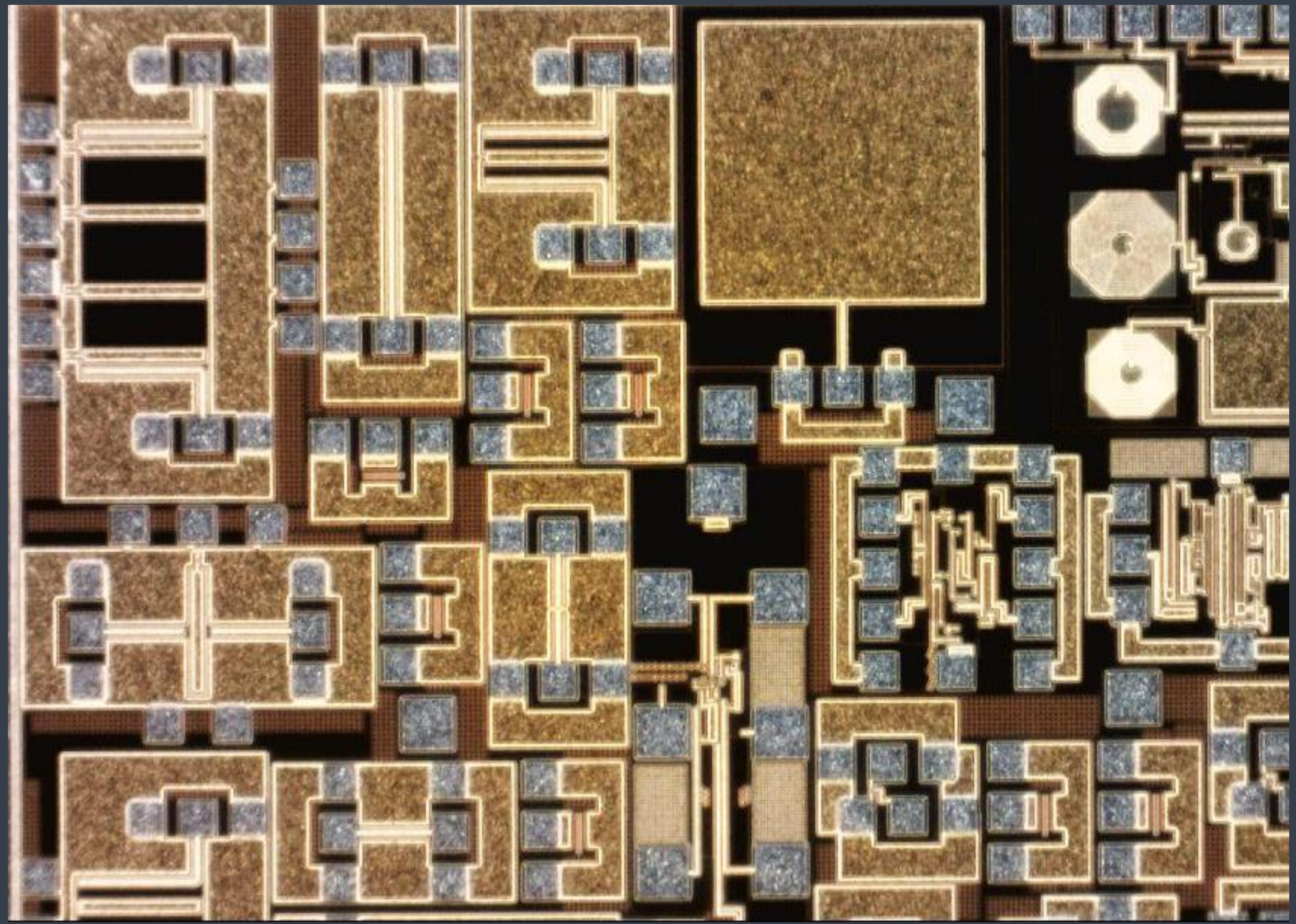
TECHNOLOGY OVERVIEW

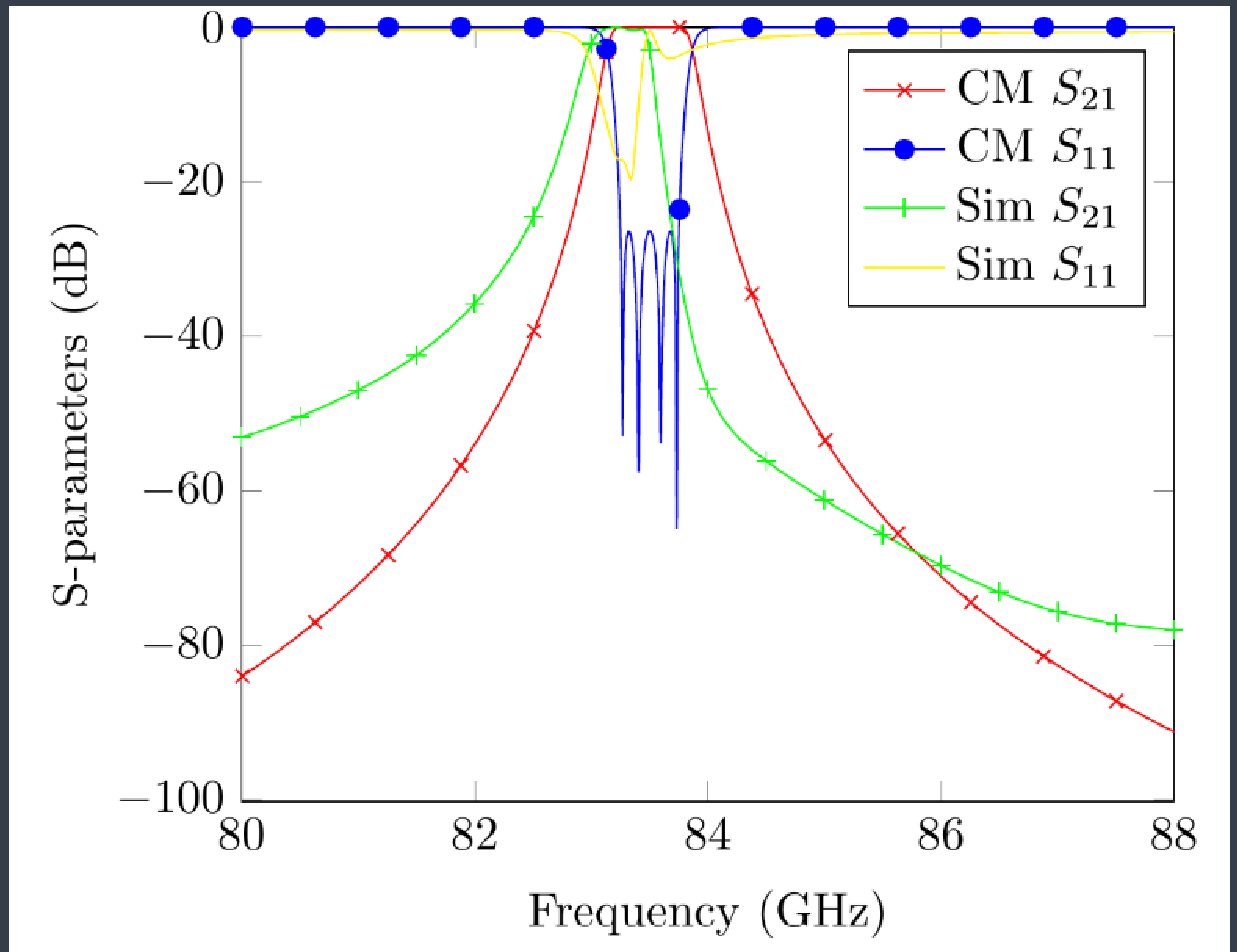
Know-how

6. Narrowband coupled resonator bandpass filters

- First narrowband on-chip mmWave BPF (can be scaled to various topologies)
- Fractional bandwidths of 0.5%
  Filters as narrow as 500 MHz
- **Applicable to E-Band 71-76 and 81-86 GHz**
- **Resonator Q_0 enhanced from 10 to 1000.**
- Opportunities for extension to a tunable BPF and/or low-noise filtering amplifier
- **Second prototype pending - pending funding**

Manufactured using: GLOBALFOUNDRIES





Simulation results of the tunable, high-Q mm-wave resonators

300 microns

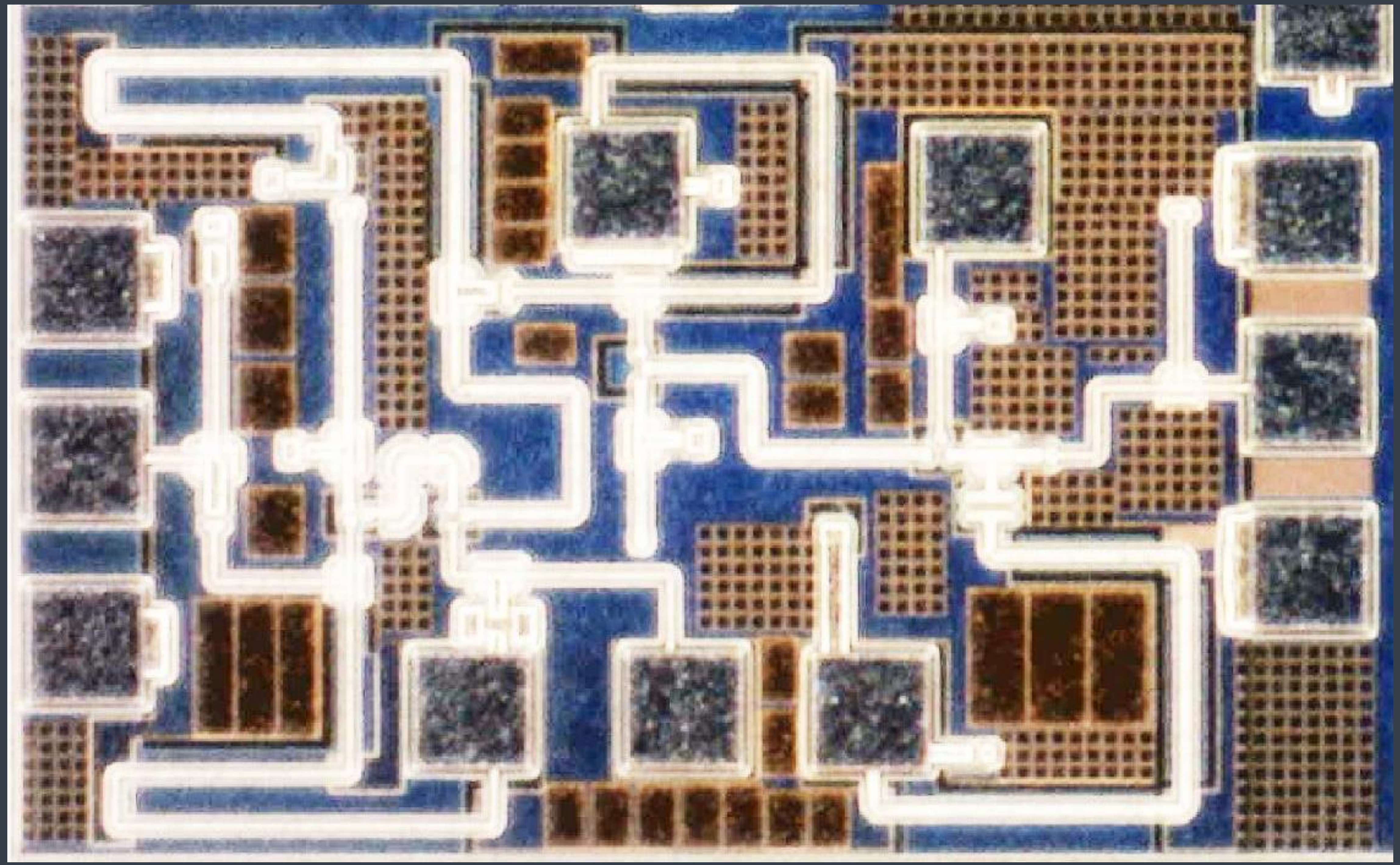
TECHNOLOGY OVERVIEW

Know-how

7. Mm-wave LNA

Manufactured using: GLOBALFOUNDRIES

- An LNA is a key component of any transceiver
- 56-92 GHz operating range
- 15 GHz bandwidth
- Gain of > 13 dB
- NF < 8 dB
- Complements Multifractal's technology portfolio enabling a future climb in the value chain
- Noise measurements pending - pending funding



Mm-wave LNA

150 microns