Future Analog Electronics and Intelligent Sensing
SIA Webinar

SIA-SRC Decadal Plan for Semiconductors

Public

Ref. SRC-SIA Decadal Plan for Semiconductors Report – released January 2021

Decadal Plan for Semiconductors - 5 Seismic Shifts

https://www.src.org/about/decadal-plan/

Fundamental breakthroughs in analog hardware are required to generate smarter world-machine interfaces that can sense, perceive and reason.

The growth of memory demands will outstrip global silicon supply presenting opportunities for **radically new memory and storage** solutions.

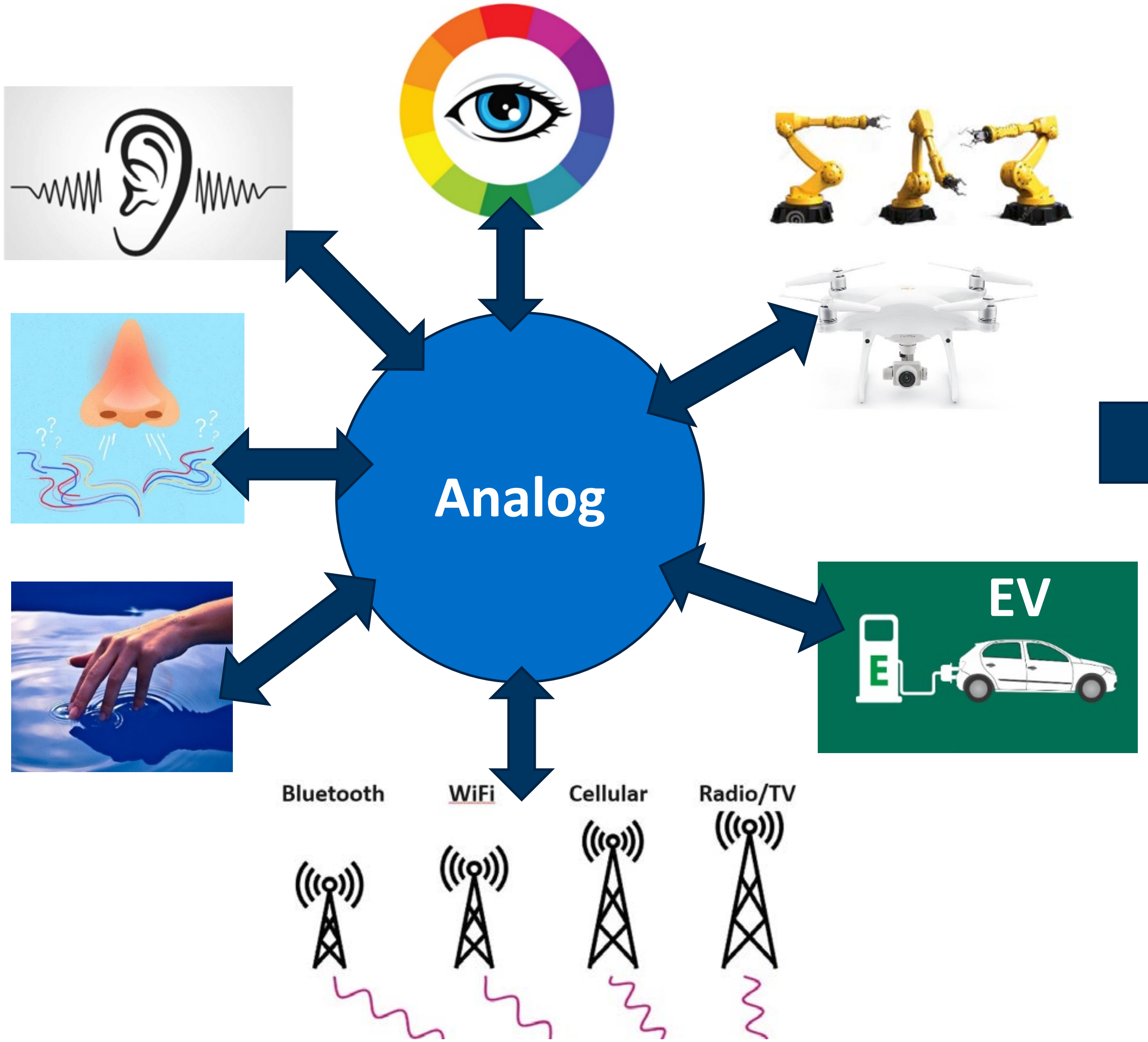
Always available communication requires new research directions that address the **imbalance of communication capacity vs. data generation rates**.

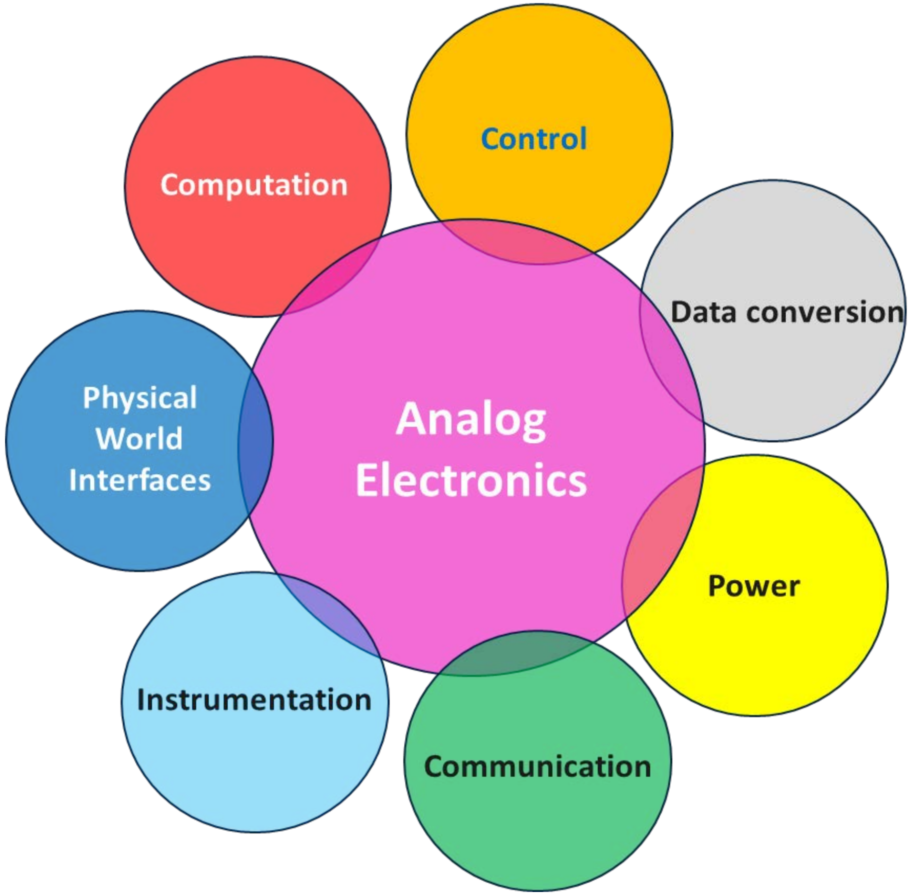
Breakthroughs in hardware research are needed to address **emerging security challenges** in highly interconnected systems and AI.

Ever rising energy demands for computing vs. global energy production is creating new risk, and new computing paradigms offer opportunities with **dramatically improved energy efficiency**.

Full Report Serves As A Guide Towards 2030 and Beyond

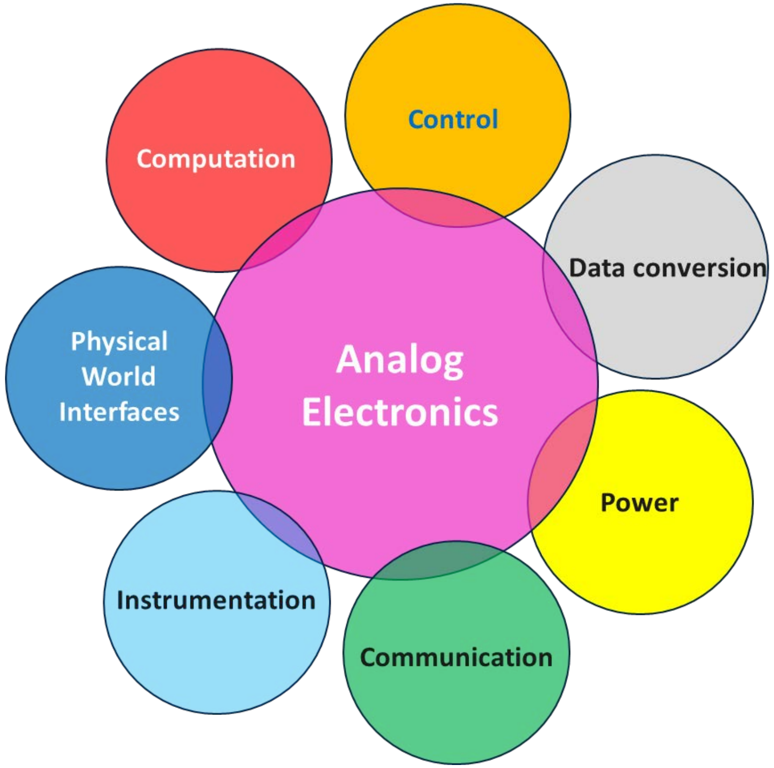
Analog is the Interface to the Real World

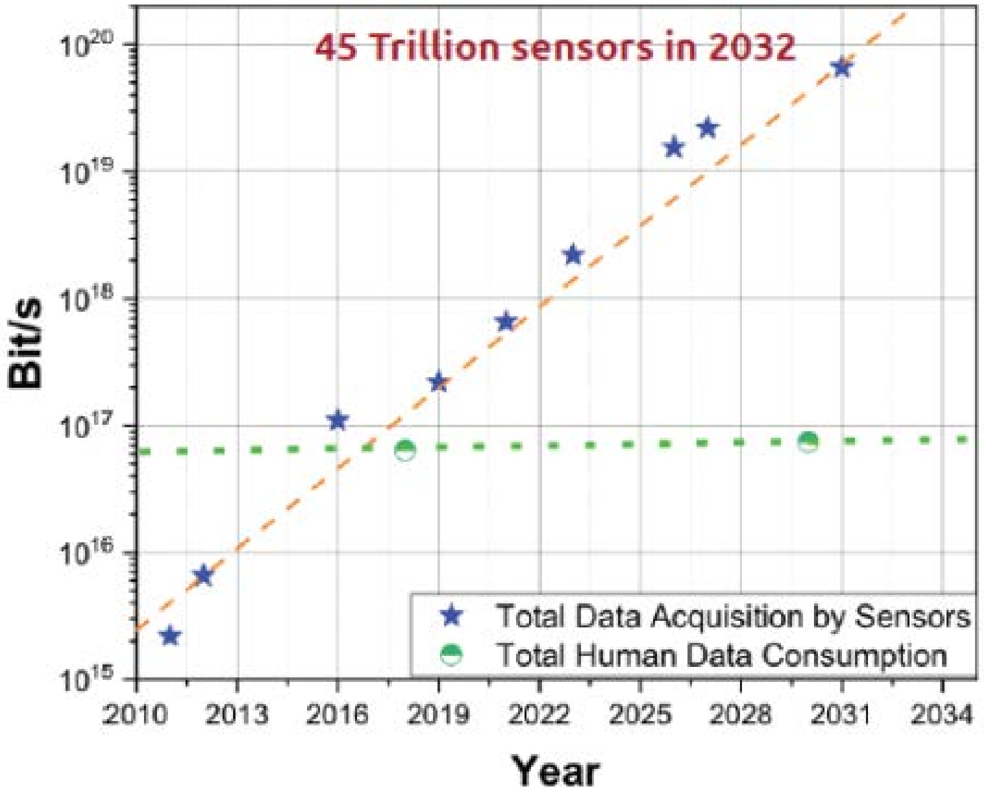




Analog and Data Deluge – Seismic Shift #1

Effectively leveraging massive analog data





Analog Grand Goal is for revolutionary technologies to increase actionable information with less energy, enabling efficient and timely (low latency) sensing-to-analog-to-information with a practical reduction ratio of ***100,000:1***

New Trajectories for Analog Electronics

"Interface to the Real World"

- **Sensing & Processing**
- **Energy Efficient Functions**
  - Communications
  - Computing/Processing
  - Power Conversion & Management
- **Bio-Inspired Model**
- **Holistic Co-Design**

Research Themes/Opportuntites

Analog-to-Digital → Analog-to-Information / Sensing to Action

Goal: 100,000:1 Data Reduction

Sensing to Action goal will not be possible without integrated system solutions with significant increase in design methods and productivity.

Trainable neuromorphic signal converters

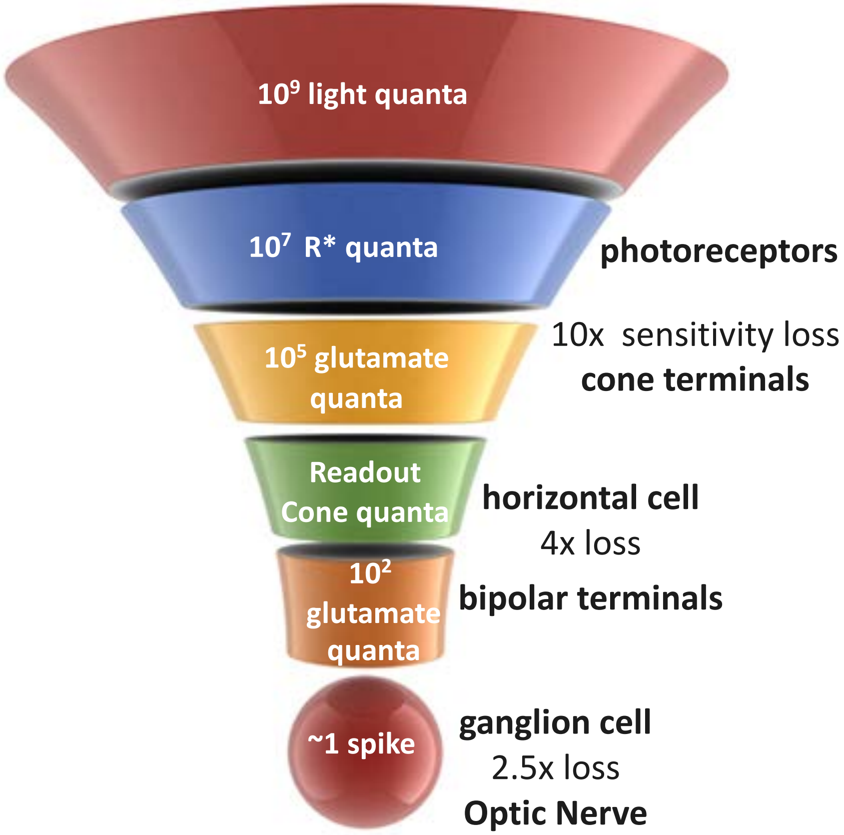
Analog Bioinspired Machine Learning

THz Regime Analog

Analog Development Methodology

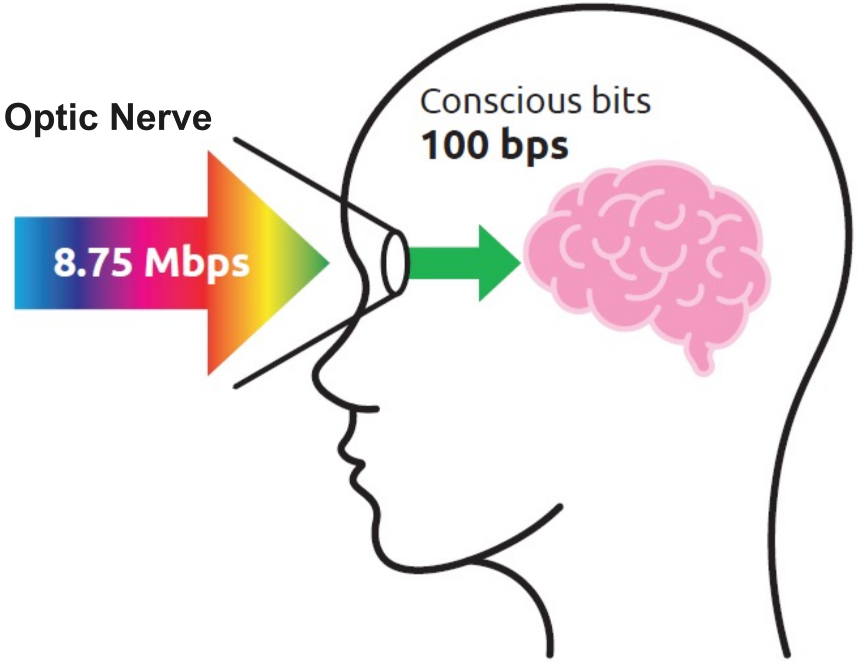
Bio-Stimulus Domain Reduction
Holistic View and Inspiration

Eye/Retina Reduction
“sensor”



Ref. “Principles of Neural Design:, Sterling and Laughlin

Processing Reduction

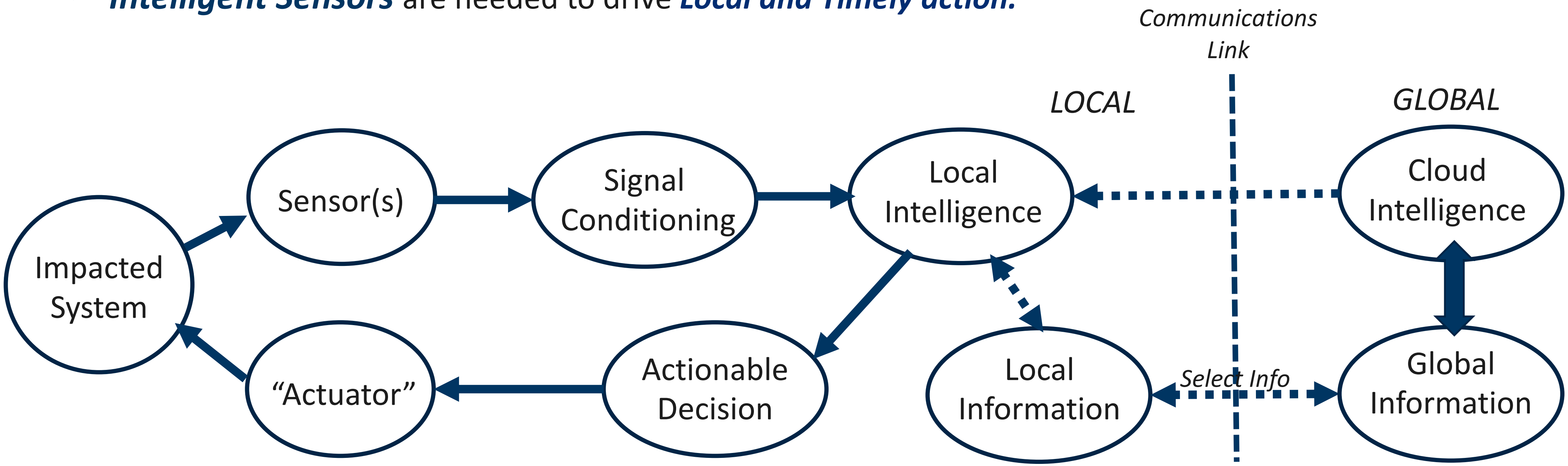


Sensory System	Bits per second	Processed by the brain (bits/s)
Eyes	10,000,000	40
Ears	100,000	5
Smell	100,000	1
Taste	1,000	1

Figure A2: Human sensory system of data acquisition via sensors

Sensing System Approach - hierarchical

- Trillions" of sensors generate redundant and unused "data."
- Cloud is not the answer.
  - Communication is a bottleneck and requires significant energy
  - Power to process redundant data is not efficient
  - Latency is too long for local control and action
- ***Intelligent Sensors*** are needed to drive ***Local and Timely action.***



Required Research – *Largest Need and Impact*

- Study of holistic solutions - with key applications knowledge and focus on minimal processing to take action
  - Collaborative multi-expertise research projects demonstrator platform(s)
  - Effective and Efficient design methods
- Heterogeneous integration - to make best use of best technology in an energy, size, and cost efficient manner
  - CMOS platform integration – optimized technologies
  - Package platform integration – multi-technology/multi-die from DC to THz
- Optimum power management – control and conversion for efficient and fast energy response and management
- Leverage human systems - as a model for bioinspired, local "sensing to action" including efficient machine learning and inference at the edge
  - Analog-based ML architectures (compute in memory, synapse, etc.)
  - Architectures and algorithms that leverage analog approach and compensate or take advantage of analog non-idealities
- Flexible, scalable, secure ***platform*** and technology - including sensors, memory, and signal representation matched to domain

Roundtable Discussion

Moderator: Dave Robertson
Senior Technology Director / Analog Devices

Introduction:

- Jim Wieser
  Director of University Research and Technology / Texas Instruments

- Kostas Doris
  Fellow / NXP Semiconductors
  Professor /TU of Eindhoven

Roundtable:

- Steven Spurgeon
  Staff Scientist, Energy and Environment Directorate / Pacific Northwest National Laboratory

- Wai Lee
  Chief Technologist, Sensing Business / Texas Instruments

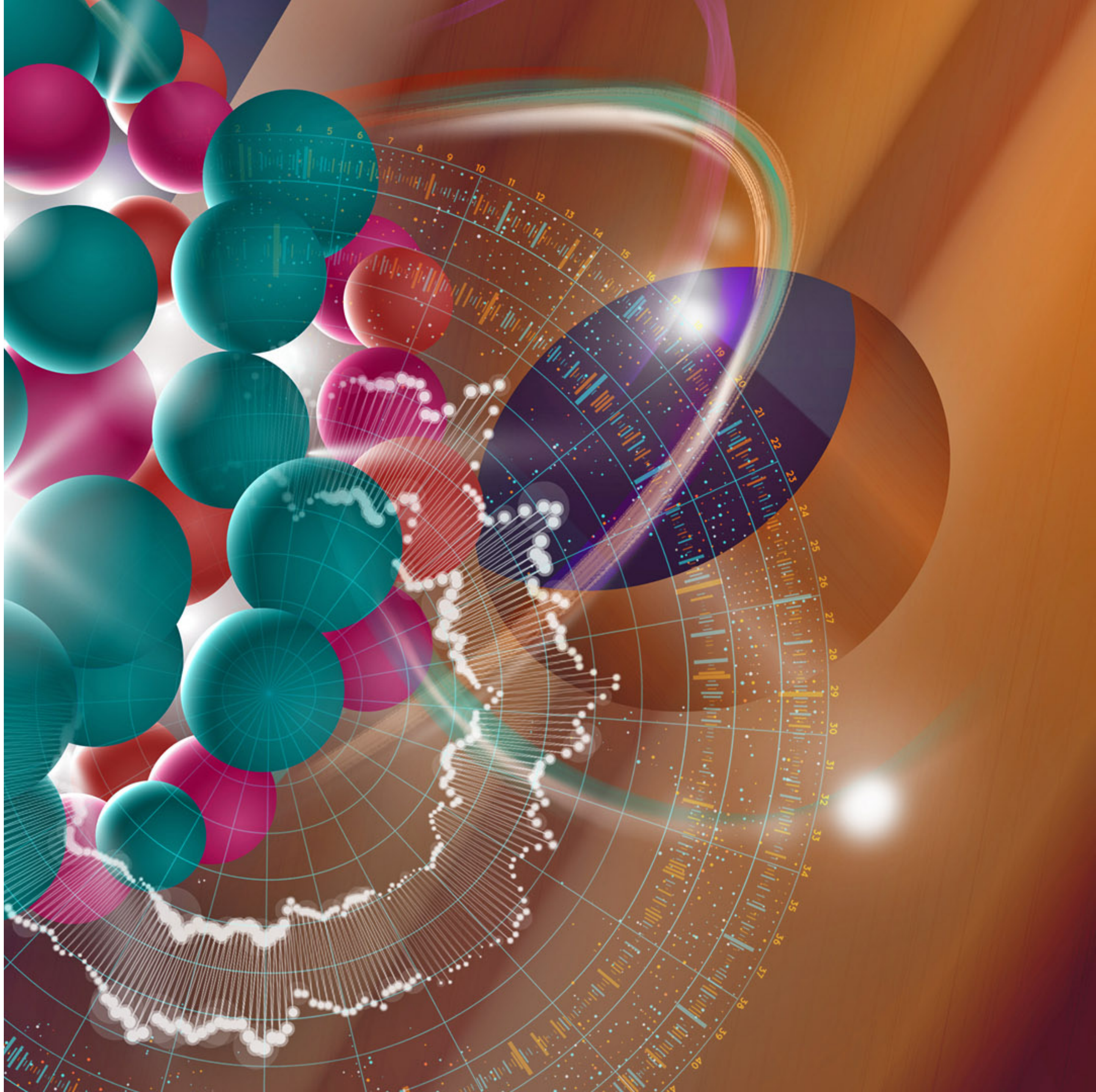
- Mark Rodwell
  Doluca Family Endowed Chair in Electrical & Computer Engineering / UC Santa Barbara

- Boris Murmann
  Professor of Electrical Engineering / Stanford University

SIA – SRC Roundtable
New Trajectories for Analog Electronics

June 10, 2021

Steven R. Spurgeon
Energy and Environment Directorate
Pacific Northwest National Laboratory

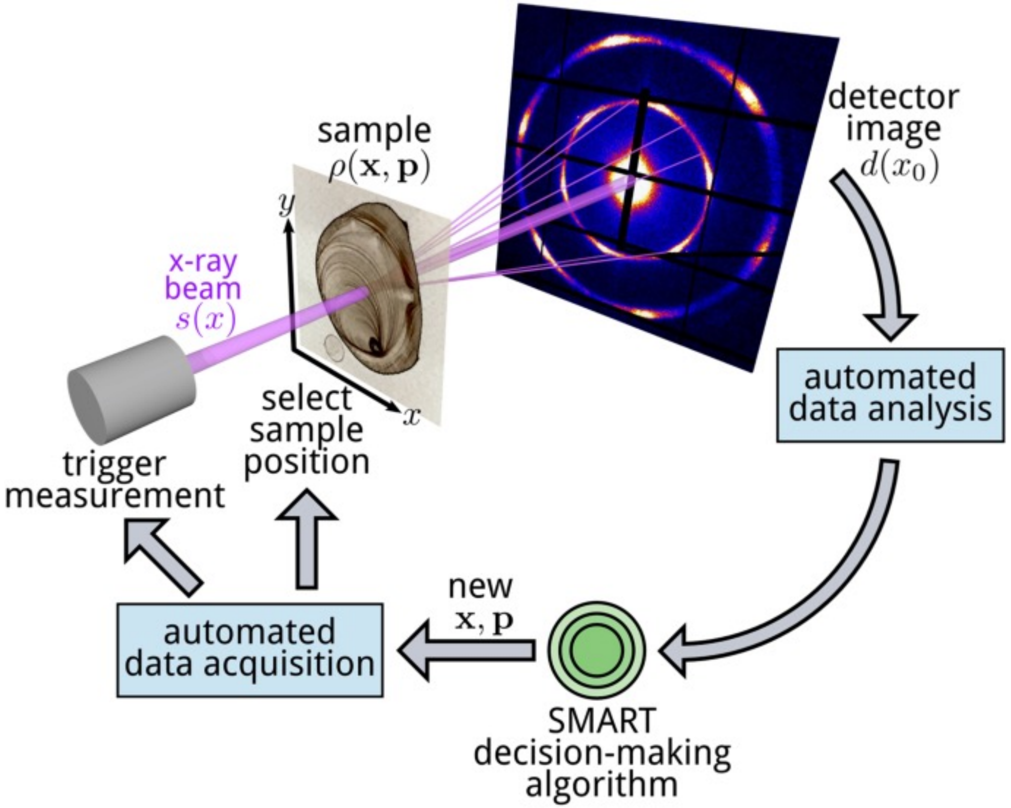


U.S. DEPARTMENT OF ENERGY BATTELLE
PNNL is operated by Battelle for the U.S. Department of Energy

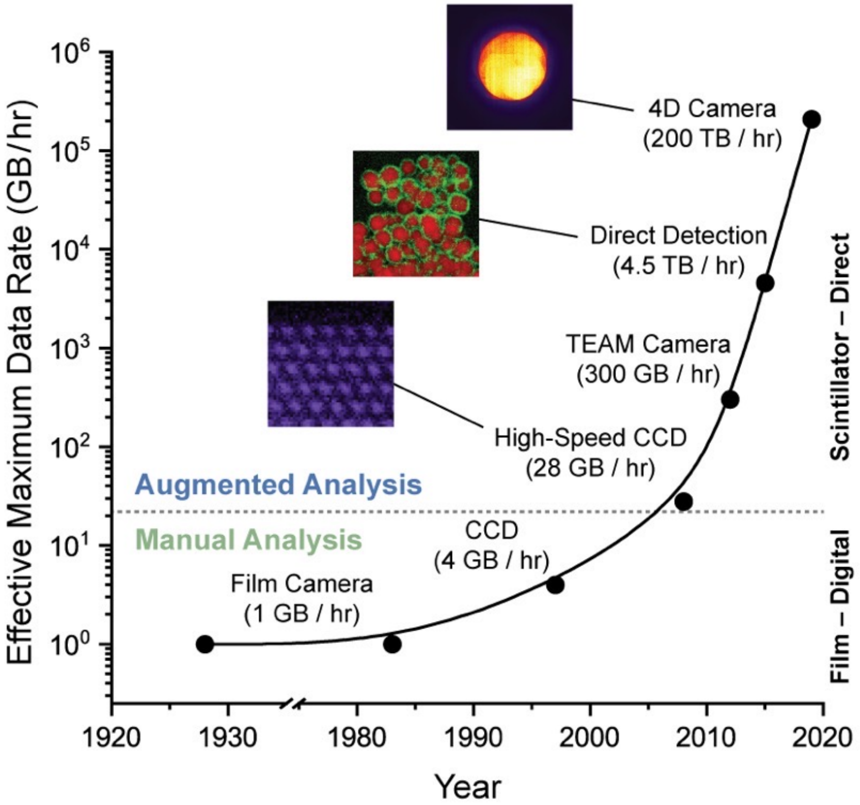
Advanced instrumentation is a catalyst for national scientific innovation and discovery.

We must develop new ways to quickly interpret and act on high bandwidth, heterogeneous data.

X-ray Scattering



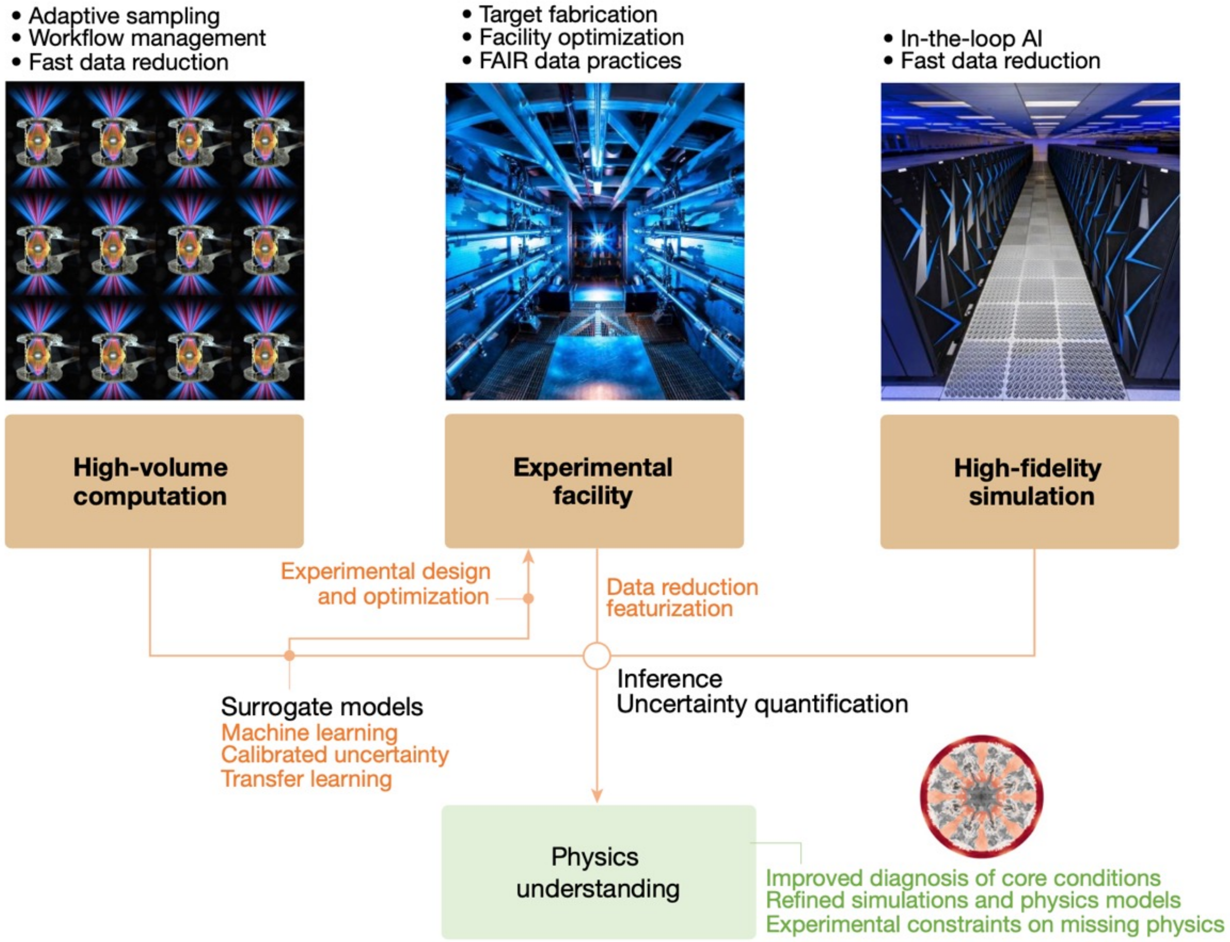
Electron Microscopy



Noack, M. M. *et al.* (2019). A Kriging-Based Approach to Autonomous Experimentation with Applications to X-Ray Scattering. *Scientific Reports*, *9*(1), 1–19. DOI:10.1038/s41598-019-48114-3

Spurgeon, S. R. *et al.* (2021). Towards data-driven next-generation transmission electron microscopy. *Nature Materials*, *20*(3), 274–279. DOI:10.1038/s41563-020-00833-z

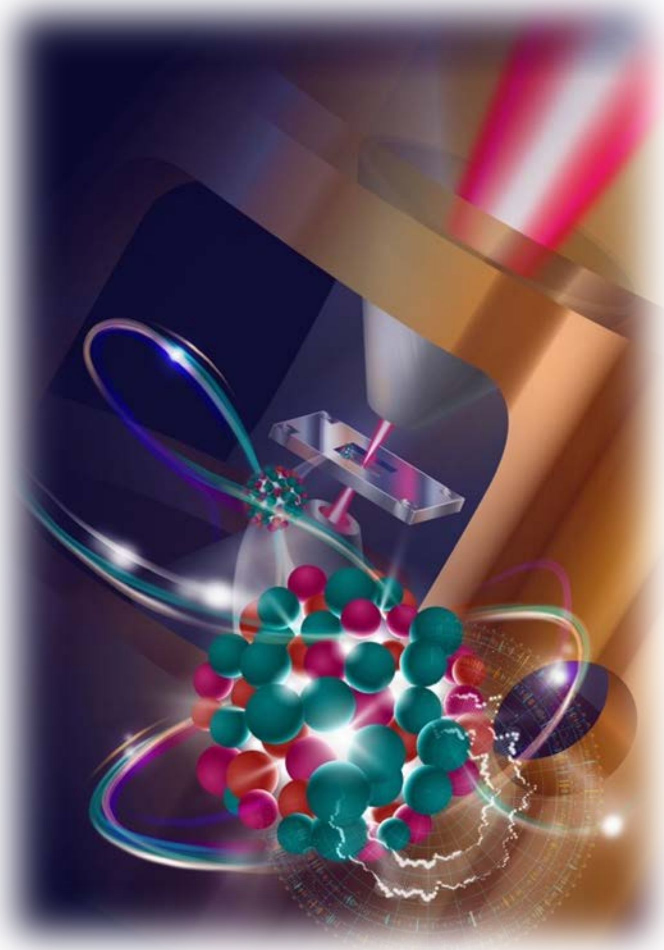
Domain-grounded reduction and inference are needed to unlock the full potential of sensors.



Hatfield, P. W. *et al.* (2021). The data-driven future of high-energy-density physics. *Nature*, *593*(7859), 351–361. DOI:10.1038/s41586-021-03382-w

Challenges and opportunities

- How can embedded domain knowledge aid in the sensing-to-action workflow?
  - Physically meaningful reduction and inference
  - Expanding intelligence to all system components
- How do we effectively harness multi-modal analog data streams?
  - Efficiency gains from data fusion/redundancy
  - Identification of unique processing solutions
- What does codesign look like in specific analytic contexts?
  - Universal vs. domain-specific designs
  - Determination of bottlenecks in data flow and decision-making process



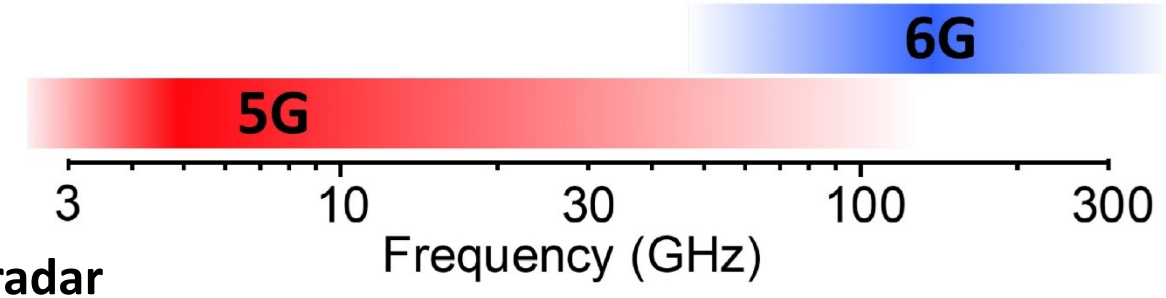
SIA/SRC Webinar - Decadal Plan for Semiconductors: New Trajectories for Analog Electronics
June 10, 2021

Transistors for Wireless

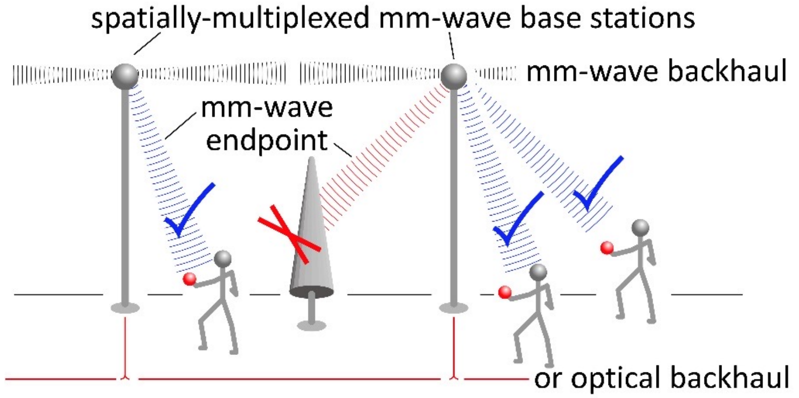
Mark Rodwell
University of California, Santa Barbara
rodwell@ece.ucsb.edu

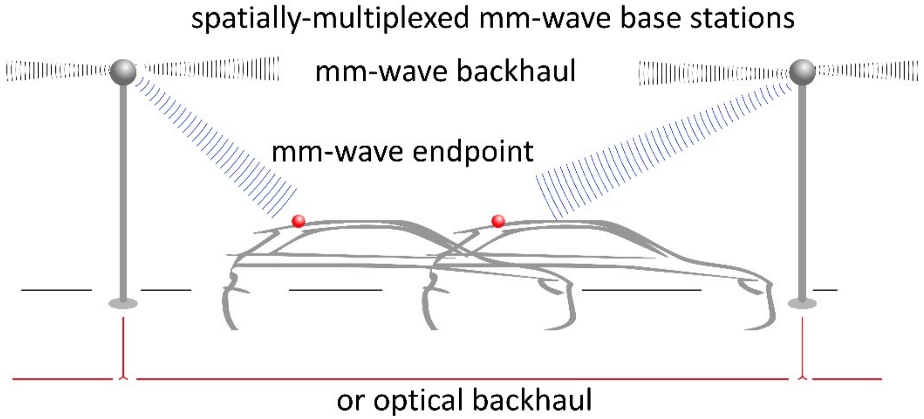
5G/6G Wireless: Terabit Aggregate Capacities

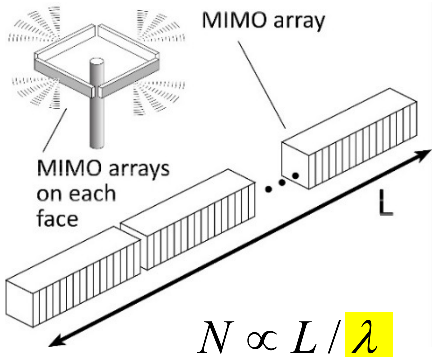
Wireless networks: exploding demand.
  High frequencies→ plentiful spectrum→ high capacity
  Short wavelengths→ many beams→ massive capacity



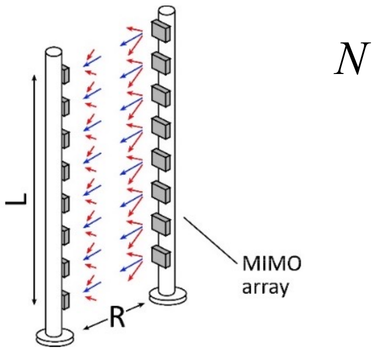
30-300GHz carriers, massive spatial multiplexing
→ Terabit hubs and backhaul links, near-video-resolution radar
Plus: 5-meter Gigabit bluetooth for many small gadgets.





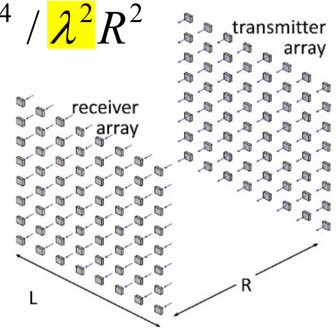


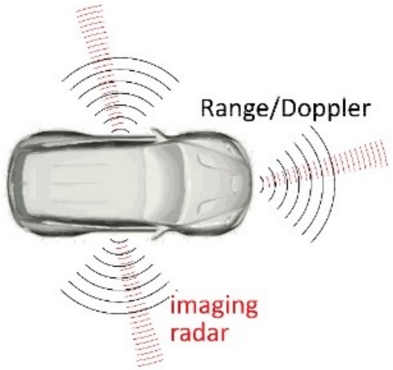
$N \propto L / \lambda$



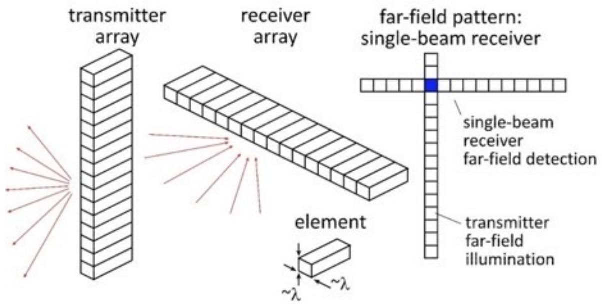
$N \propto L^2 / \lambda R$

$N \propto L^4 / \lambda^2 R^2$





$\Delta\theta \propto \lambda / L$



CMOS alone won't do it

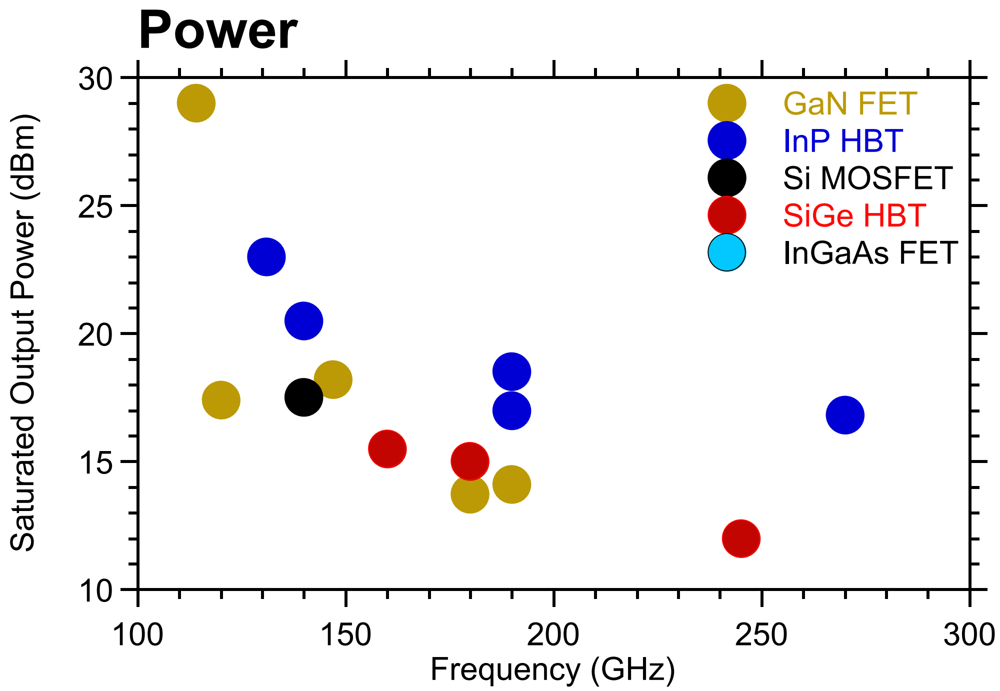
Wireless needs: low noise, high power & efficiency.

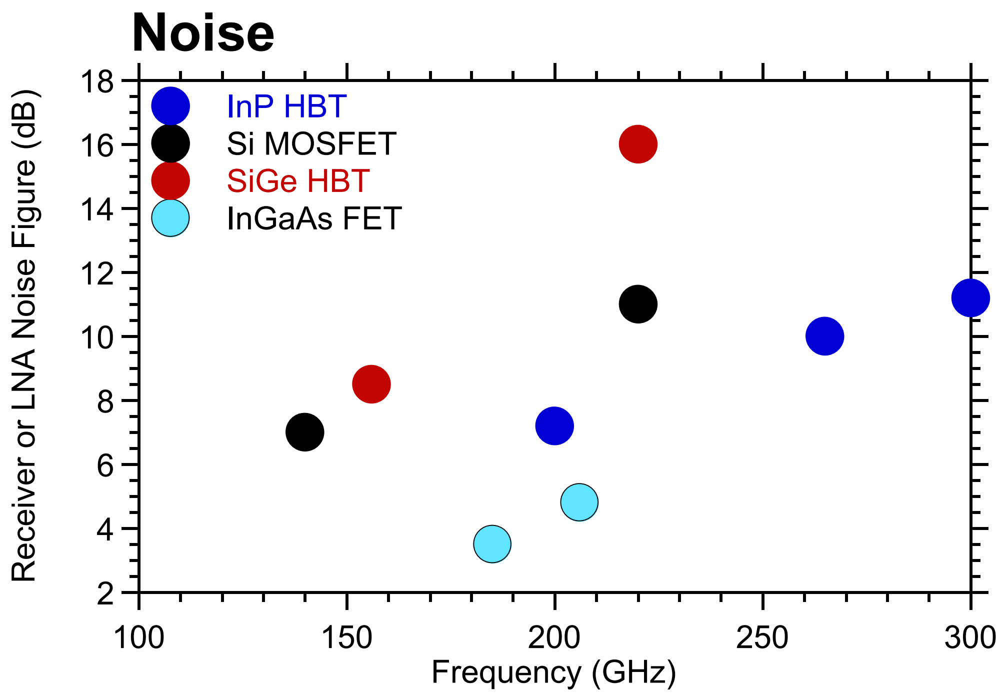
VLSI CMOS: compromised on all 3.

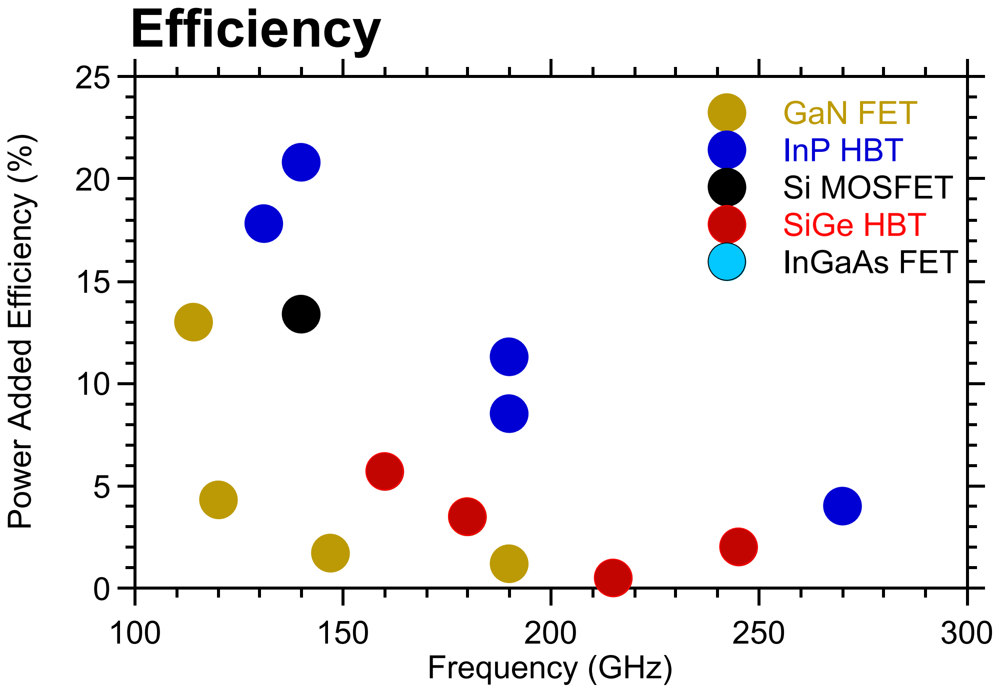
Dennard's scaling laws are broken.

CMOS: optimized for VLSI, not wireless & analog**.**

CMOS: needs help to cover moderate distances**.**







What wireless needs

Need technology mix: CMOS + (InP, SiGe, GaN)

Cheap but High Performance

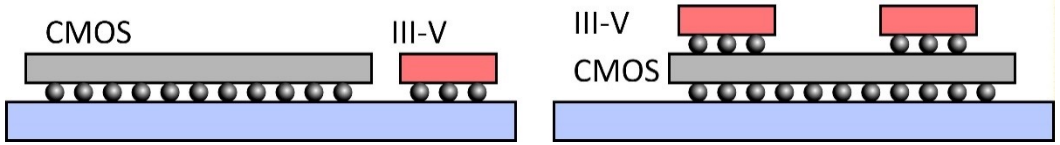
Receiver noise: 3dB less noise saves 2:1 transmitter power.
Efficient transmitters : 30% is bare minimum
Powerful transmitters: (0.1W arrays, 1W single beam)
Not just better transistors: interconnects matter
Cost: What is cheap today? What could be made cheap if we tried ?

Needed: Application-specific wireless IC technologies

high-volume, low-cost InP HBT, InP HEMT, near-THz SiGe,
wireless-optimized CMOS (e.g. GF 45nm SOI, Intel 22FFL)

Needed: heterogeneous integration (very dense packaging)

CMOS plus (SiGe, III-V chiplets).
integration density, heat, production III-V.



HETEROGENOUS AND CO-FUNCTIONAL INTEGRATION NEEDS, OPPORTUNITIES, CHALLENGES

SRC Analog Trajectories

Kostas Doris

JUNE 2021

SECURE CONNECTIONS FOR A SMARTER WORLD

PRELIMINARY NOTE

- Precision and reliable sensing needed in many emerging applications
  - Robotic/industrial, agriculture, drone, safety, medical, 6G Telecom
- This talk focusses on sensing for Automotive without loss of generality

A few messages to take away from this talk

1. **We need sensors that generate more information not more data. This means smaller wavelengths and more functionality in the sensor are needed.**

2. **In-package integration is the new cauldron of integration like CMOS technology was in the past.**

3. **Many heterogeneous technologies and functions must be conditioned optimally together to the perception function.**

AUTONOMOUS DRIVING NEEDS MULTIPLE SENSOR MODALITIES

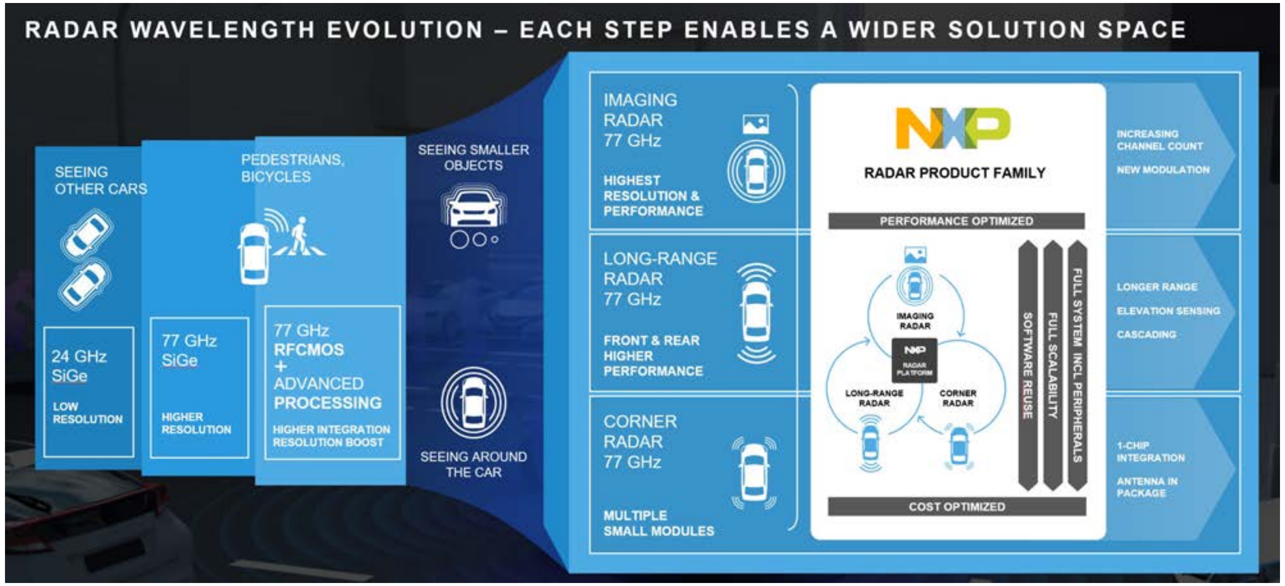
TECHNOLOGY COMPLEMENTARITY AND REDUNDANCY IN PERCEPTION

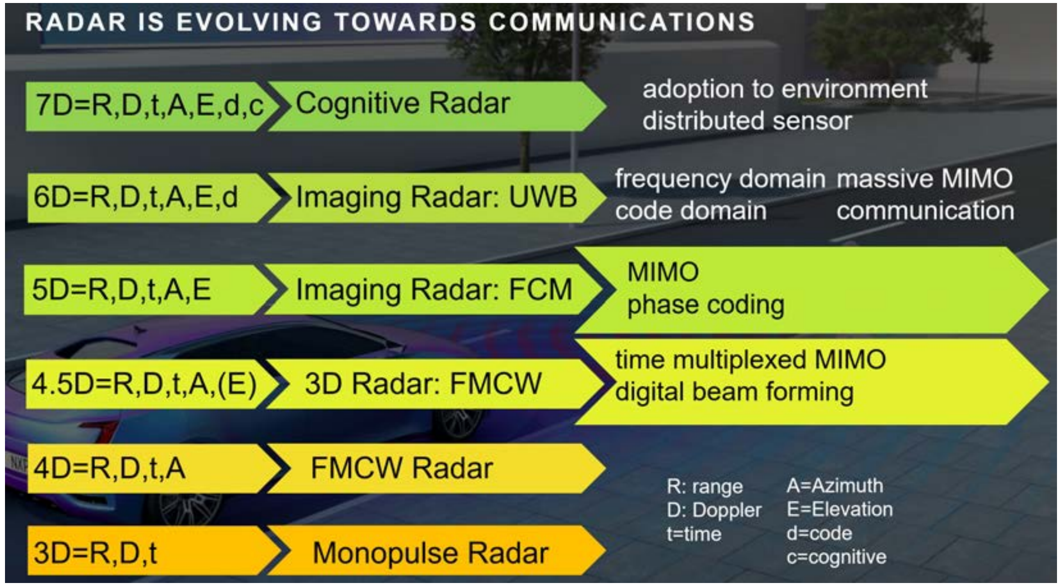
	Camera	LiDAR	Radar	Fusion
Distance Ranging	*Indirect*	*Time of Flight*	*Time of Flight*	
Speed Measurement	*Indirect*	*Indirect*	*Direct Doppler*	
Angular Separation	*Megapixels*	*0.1° - 0.25°*	*1° - 3°*	
Colour Patterns	*Traffic Signs & Lines*	*Intensity only*	*No*	
Adverse Weather/Light	*Very Limited*	*Limited*	*See through rain, fog, snow, night, sun*	
Output Data	*2D Image*	*3D Point Cloud*	*4D Target List*	*Complete 360° Perception*
Best For	*Recognition of Objects, Signs, Lanes*	*Freespace / Boundary Detection, Localization*	*All-weather distance & speed measurement*	*Autonomous Driving L3+*

- No Sensor is perfect: the one sensor sees what the other does not see
- Functional Safety requires diversity in failure modes
- The path for affordable LIDAR keeps going on …

Is it that simple? Lidar, Radar, Camera?

ZOOM-IN AUTOMOTIVE RADAR EVOLUTION



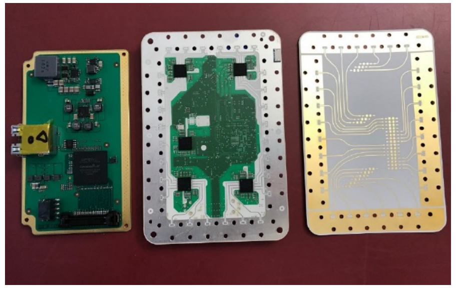


Enablers of 77GHz solution space expansion

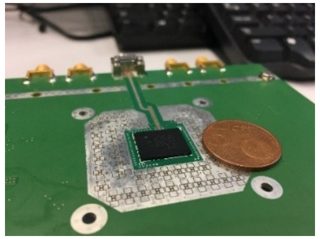
Mm-wave CMOS & ADC/CHIRP technology-front push

One chip MIMO MMIC and Radar DSP size reduction

Pathway to cascading/MIMO



3D WG/Antenna.



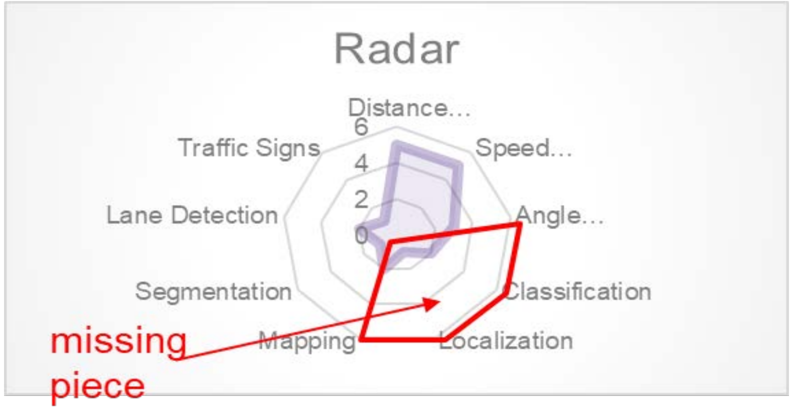
Mm-wave packaging

/ Antenna-in-package

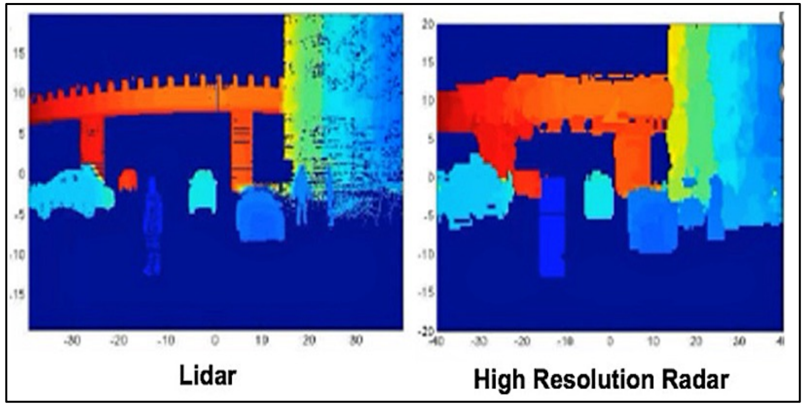
Beginning of in-package integration

Much more is needed!

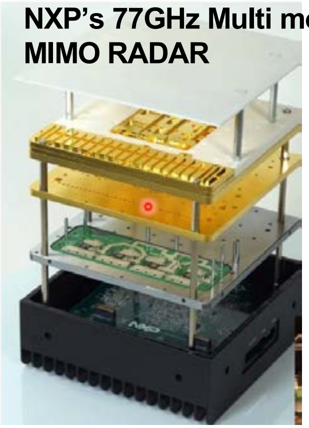
RADAR / SENSING NEEDS AND 77GHZ BAND LIMITATIONS



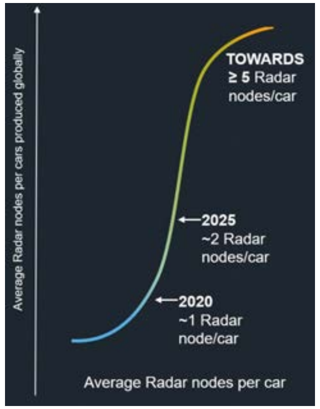
Mapping, localization, classification

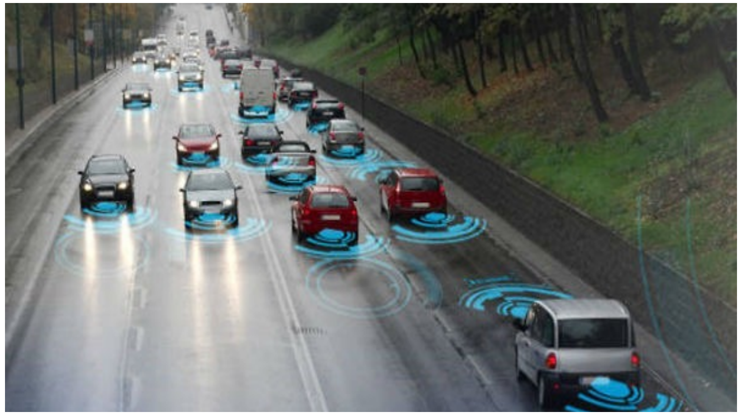


”Lidar like” angular resolution,
360d view, Elevation



Size reduction



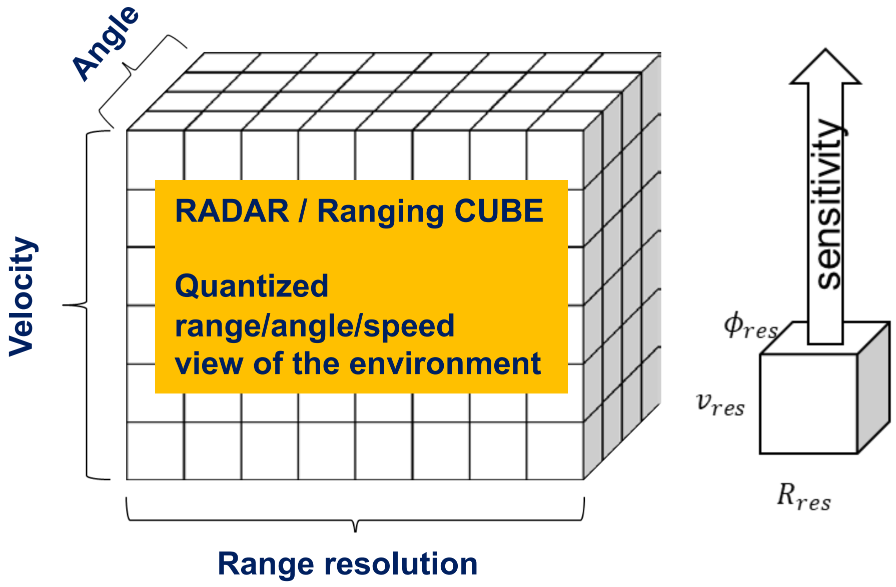


Interference management needed!
Advanced waveforms in conflict with FMCW.

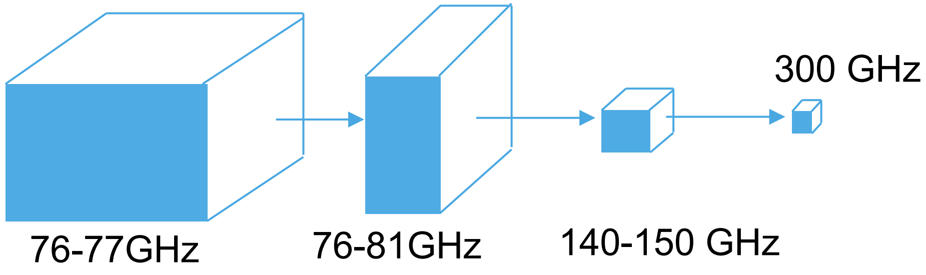
Multiple limitations at 77GHz:

- **Fixed dimensions limits angular resolution**
- **Bandwidth regulations and application defined (safety) radar cycle time limit range resolution**
- **Resolution, Angle, speed tradeoffs**
- **MIMO scalability / waveform orthogonality**
- **MMIC power consumption**

IMPROVING RESOLUTION - OPPORTUNITIES AND CHALLENGES

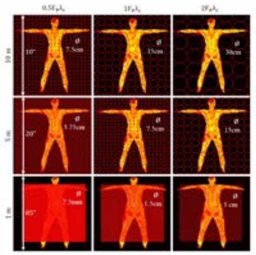


Mm-wave Ranging evolution



Mm-wave Imaging

10m passive imager view
[S.v.Berkel, TU Delft]

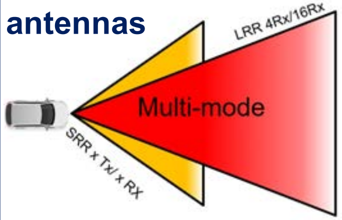


- Adoption of smaller wavelengths enables fundamental step in resolution and size reduction.
- More information classes become available!
- Finer sensor granularity possible: Ranging , Radar-Imaging, Camera, Light Ranging.

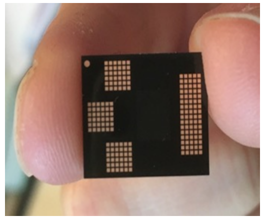
Challenges ahead: Link budget, massive MIMO complexity, data rate explosion, no tech that does it all, power/heat management, manufacturing, reliability, cost…

HOW TO GET THERE – RESEARCH DIRECTIONS

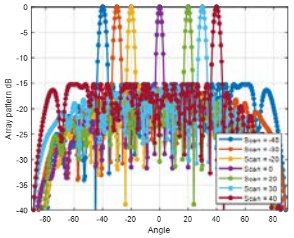
Electronic multi-mode antennas



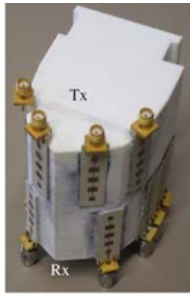
Array-in-package



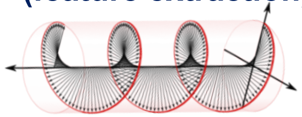
Sparse arrays



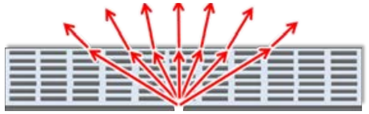
Conformal antennas

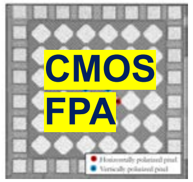


Polarimetry (feature extraction)



Mm-wave lenses Optical techniques



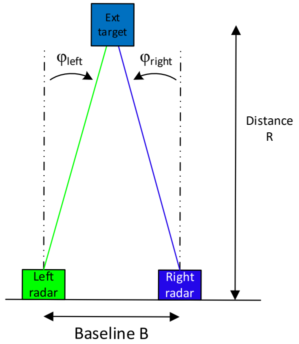


Massive MIMO Time, frequency, code

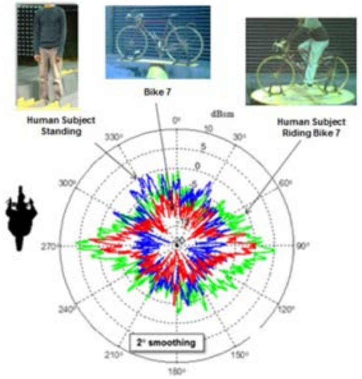
Compressive Sensing

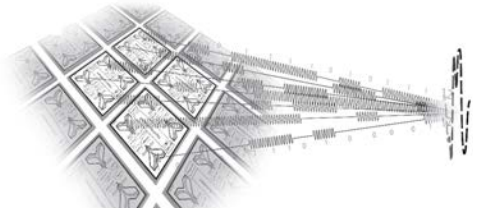
Explore channel behavior wavelenths

Distributed radar



Radar image Processing with A.I. Enhanced classification





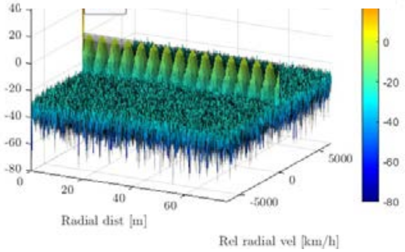
multiple functions, in-package integration, multiple nodes advanced DSP: all conditioned together to the sensing function!

Mm-wave signal generation RFCMOS? SiGe? Efficiency, reliability, Noise

Arbitrary Waveform generators supporting radar signatures

Synchronization in massive arrays

Full duplex / echo cancellation for MIMO

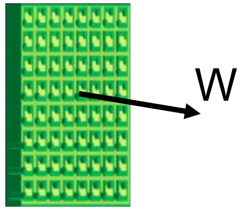


Context/feature extraction in Analog to Digital

- ✚ **mm-Wave Tech Nodes, Grade1/150C**
- ✚ **Antenna/Waveguide, Passives, Lenses**
- ✚ **More radar DSP, more channels further CMOS scaling**

Panel & System-in-Package/ 3D integration

- mechanical, tolerances,
- Heat management, mm-wave routing



System partitioning – electrification trends

Intelligent Sensing and Sensor Fusion: Opportunities and Impacts

Wai Lee

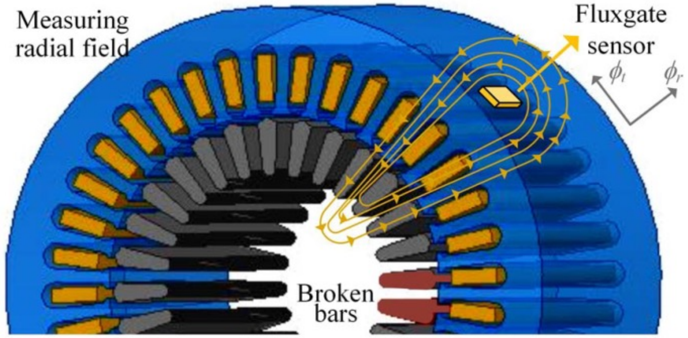
Chief Technologist, Sensing Products

Texas Instruments Inc.

June 10, 2021

Multi-modal Sensing and Sensor Fusion

- Example: motor health monitoring
  - Multiple sensing modalities: Vibration, temperature, magnetic flux, and current
  - Yet to be accomplished:
    - Edge processing helps to minimize the energy used for data transmission to the cloud, allowing battery operated sensor nodes
    - Edge (local) sensor fusion to make timely decisions and interact with motor control
    - AI techniques to enable failure pattern recognition
    - Self monitoring sensors themselves for reliability
    - Security intelligence

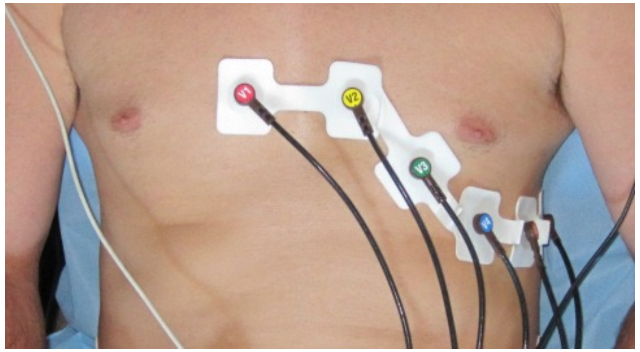


Source: Prof. Akin, UTD, SRC Task 2810.016

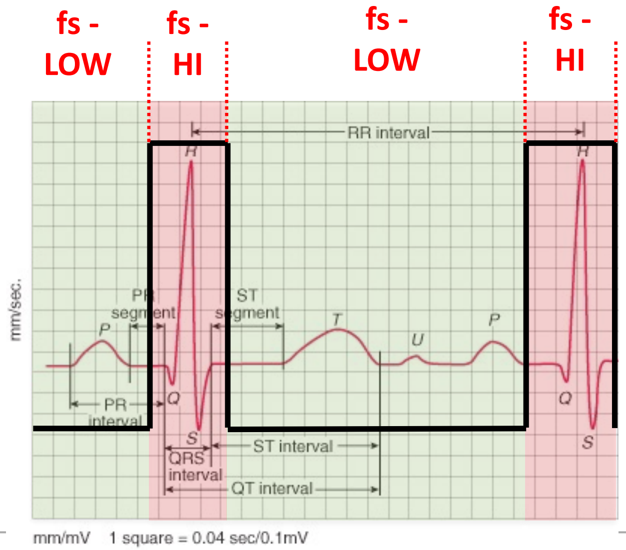
- Innovation opportunities in next decade:
  - Sensor fusion at the edge
  - A2I, rather than A2D
  - Compressive sensing with multiple sensing modalities
  - Self health monitoring of sensors
  - Low complexity and energy efficient algorithms for pattern recognition and data security

Compressive Sensing and A2I

- Good progress in compressive sensing in past decade, demonstrating significant power savings in imaging, audio, and health applications

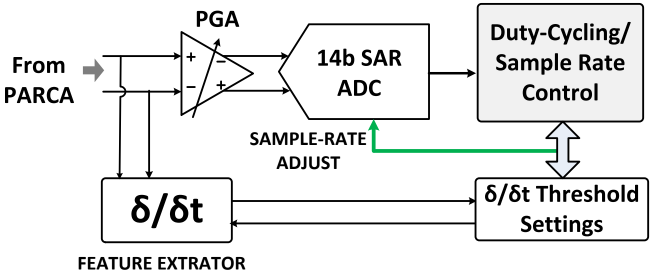


Wearable ECG
~10x power reduction by adaptive sampling



Low Importance

High Importance



Source: Sharma, et al, IEDM 2016

- Innovation opportunities in next decade
  - Most compressive sensing techniques are application specific. How do we make them more general purpose by having more intelligence?
  - System level optimization to determine “I” for A2I
  - Flexibility vs optimization tradeoffs

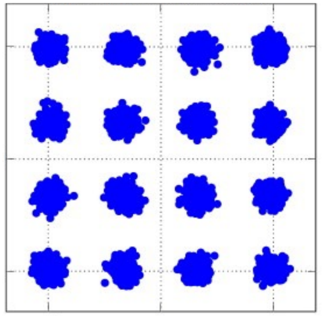
New Trajectories for Analog Electronics

Boris Murmann
June 10, 2021

Stanford | ENGINEERING
Electrical Engineering

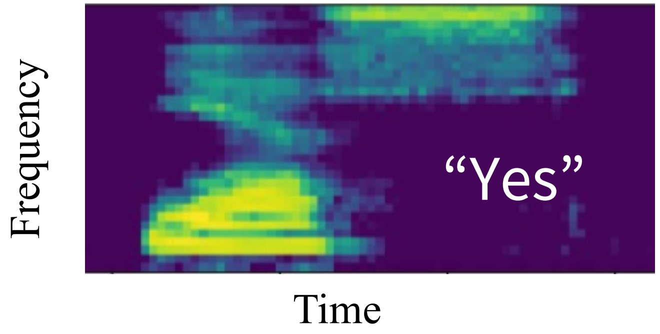
murmann mixed|signal

Communication



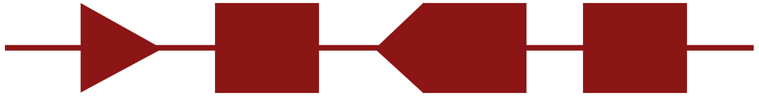
- Info bits per sample = large
- OK to digitize each sample

Inference

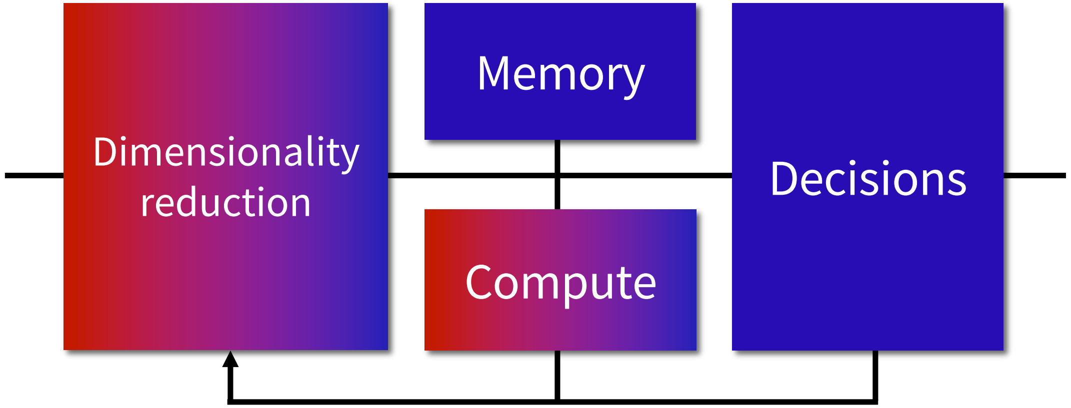


- Info bits per sample = very small
- Human speech: ~39 info bits/sec
- Full digitization: ~hundreds kbits/sec

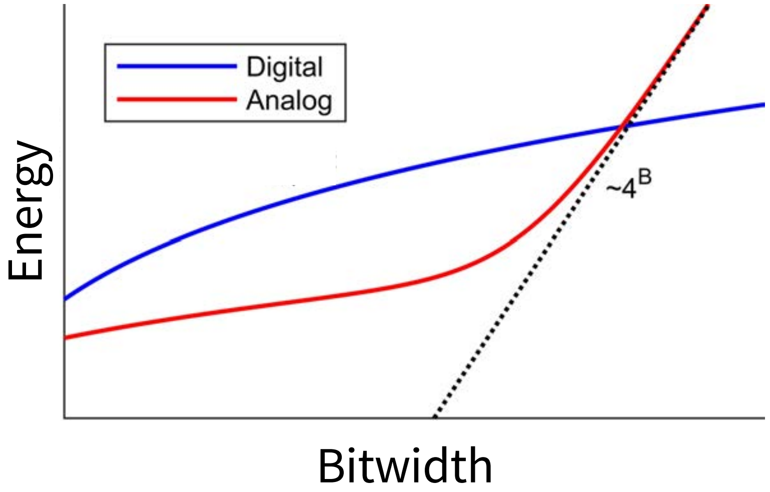
Hard to justify use of “same old” A/D interface for inference

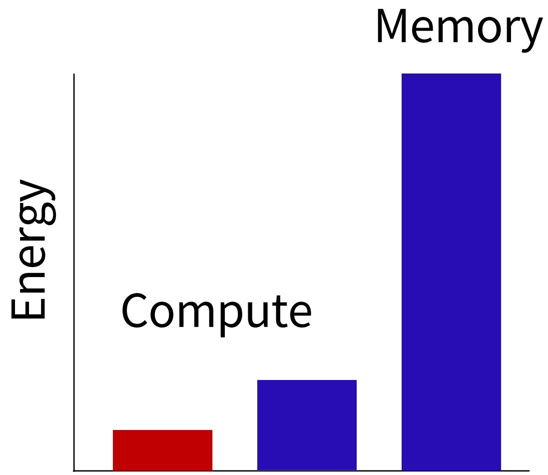


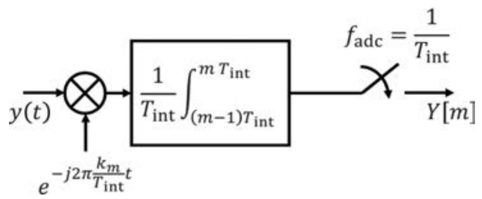
Interfaces 2.0



- Domain-specific and "data driven" architecture design
- Minimize data conversions, data movement, memory access
- Combine strengths of analog & digital for low-energy processing





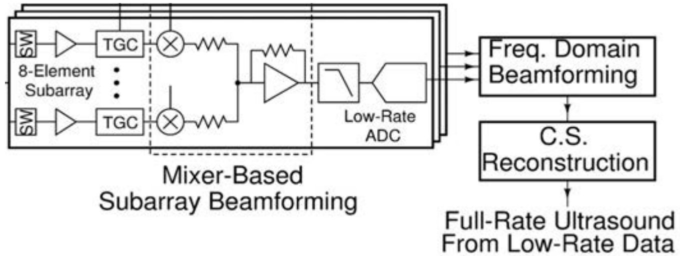


30x

Predistorter spectrum sensing
Hammler, TCAS1 2019

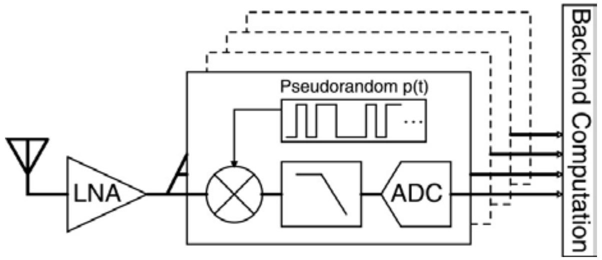
25x

Log gradient imager
Young, JSSC 2019



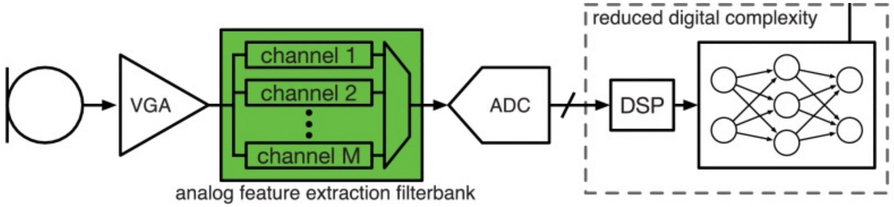
43x

Sub-Nyquist ultrasound
Spaulding, IUS 2015



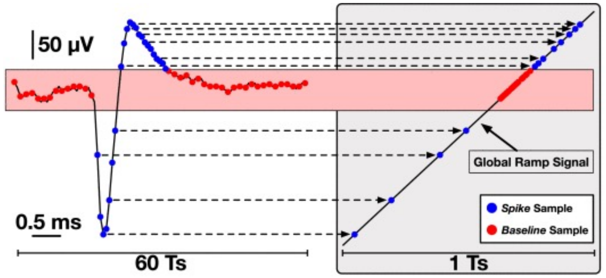
180x

RF spectrum sensing
Adams, JSSC 2017



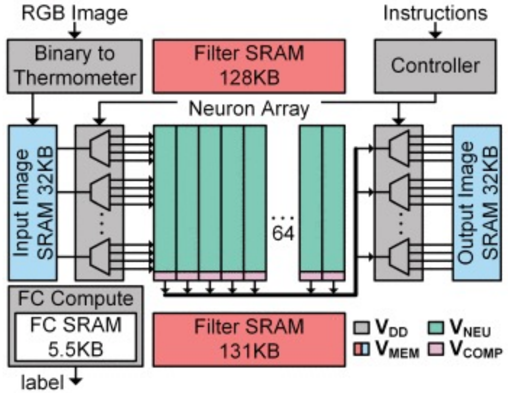
1000x

Audio feature extraction
Villamizar, TCAS1 2021



40x

Compressive neural recording
Muratore, TBioCAS 2019



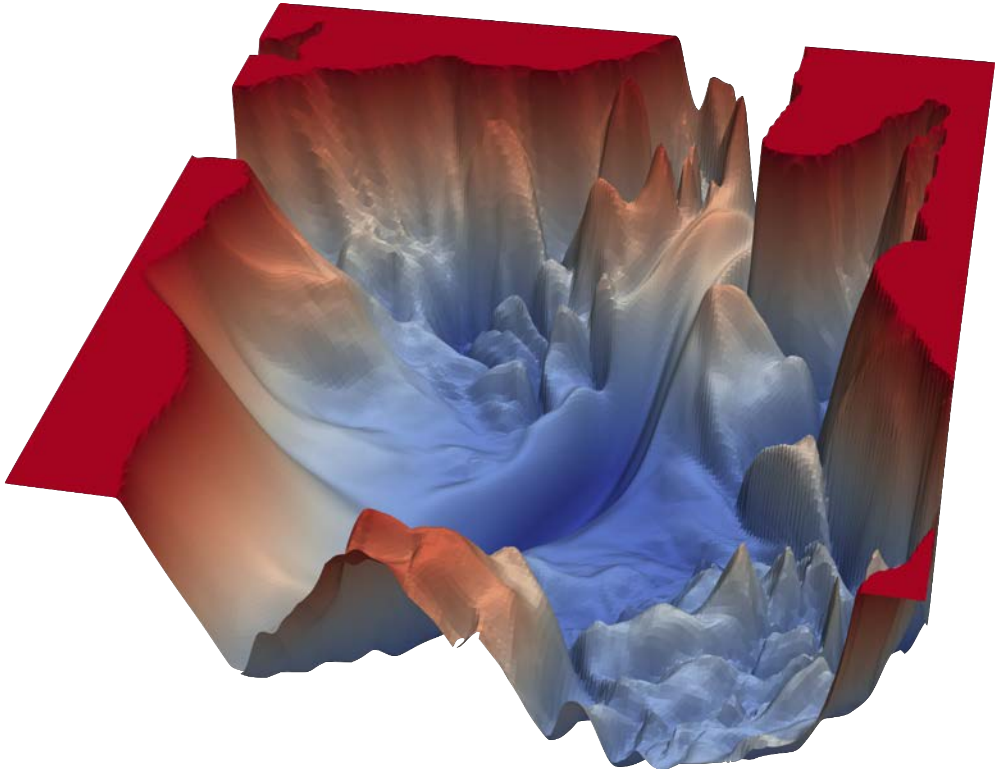
772 1b-TOPS/W

Mixed-signal neural network
Bankman, JSSC 2019

Challenges and Research Needs

- How to generalize and amortize R&D effort across multiple applications?
- How to determine analog block requirements without running huge number of CPU cycles?
  - Much easier for Interfaces 1.0
- How to link architecture search to relevant low-level circuit specs?
  - Example of an insufficient proxy: Number of neural network model weights
- How to educate next generation IC designers to embrace higher levels of abstraction?

The world is complex in high-dimensional space…



Loss landscape of a neural network

https://www.cs.umd.edu/~tomg/projects/landscapes/

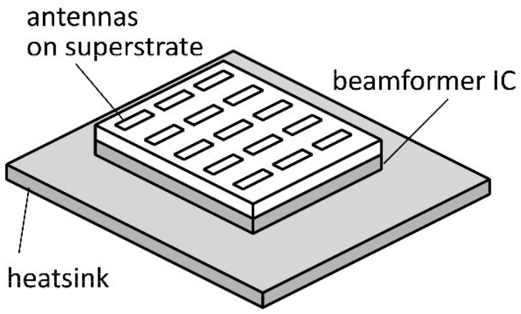
2nd Discussion Phase

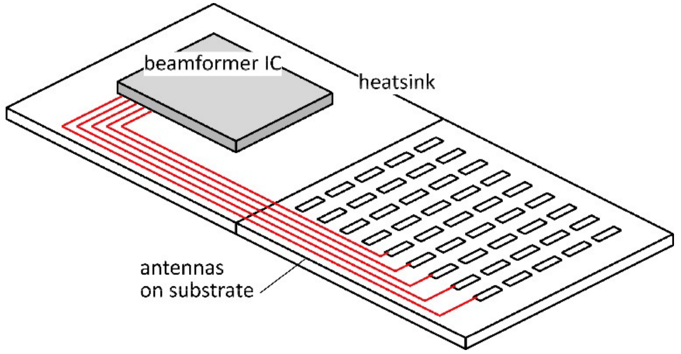
The mm-wave packaging problem

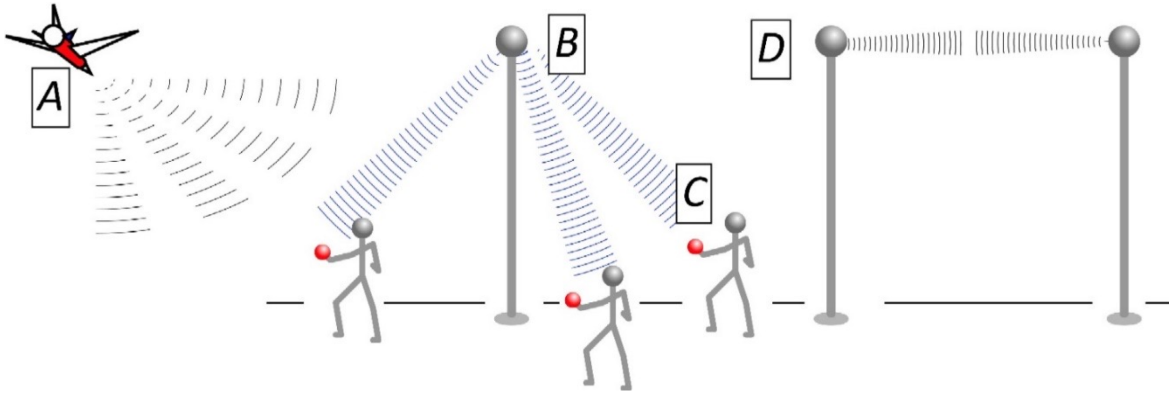
How to make the IC electronics fit ?
How to avoid catastrophic signal losses ?
How to remove the heat ?

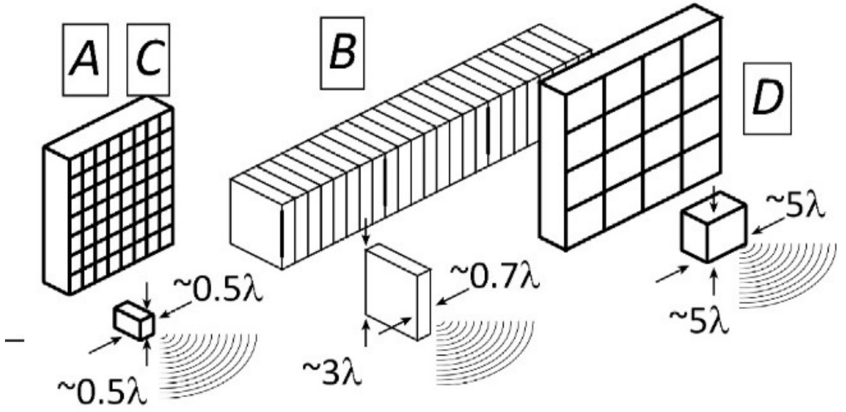
Not all systems steer in two planes...
...some steer in only one.

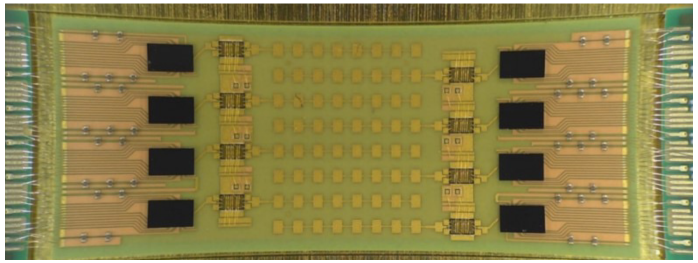
Not all systems steer over 180 degrees...
...some steer a smaller angular range

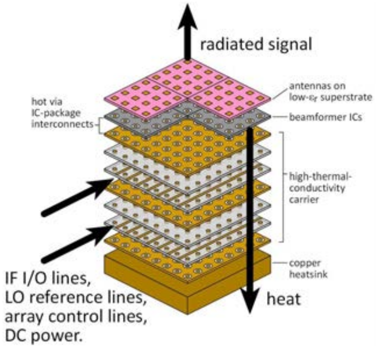


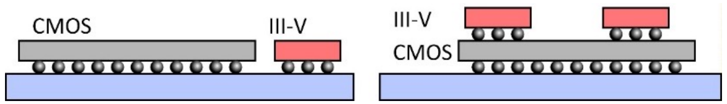


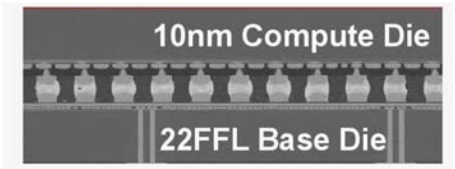












Future wireless: many, many low-power channels

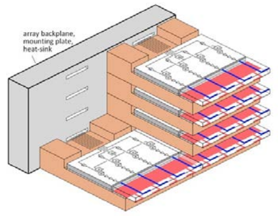
More & more channels @ lower (RF power, DC power, area, cost) /channel,

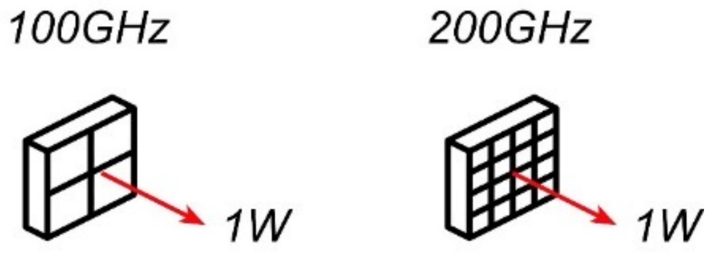
$$P_{received} = \frac{A_t A_r}{\lambda^2 R^2} e^{-\alpha R} \cdot P_{trans} \longrightarrow \#\text{beams} \cdot (\text{bit rate per beam}) \cdot kTF \cdot \text{SNR} = \frac{A_t A_r}{\lambda^2 R^2} e^{-\alpha R} \cdot P_{trans}$$

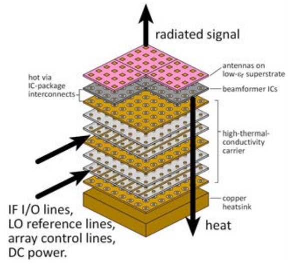
Proposed scaling law	change
carrier frequency	increase 2:1
aperture area	keep constant
total transmit power	keep constant

→

Implication	change
capacity (# beams·bit rate per beam)	increases 4:1
number elements	increases 4:1
RF power per cm² aperture area	stays constant
RF power per element	decreases 4:1







High-frequency arrays : vast #s of elements, small area per element, low RF power per element
Need: dense mm-wave IC design → High gain/stage, small passive elements
Need: low-power mm-wave IC design (mixers, LNAs, $\Delta\phi$…)→ high gain/stage, ultra-low V_{DD},…
Need: efficient back-end processing; massive #s of low-SNR signals. New digital beamformer designs
Need: new low-precision array architectures.

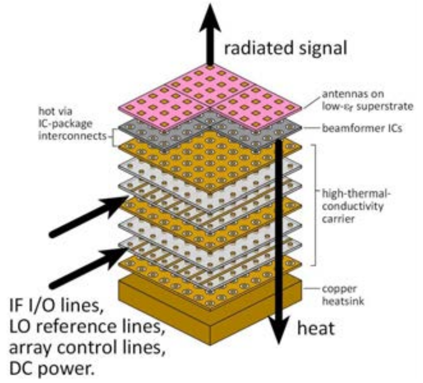
Advanced interconnects: not just for VLSI

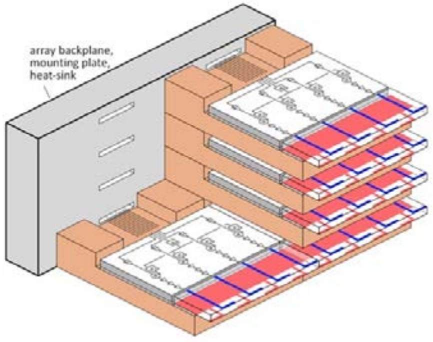
5G/6G needs high-performance IC interconnects
low interconnect losses
high interconnect & passive element density

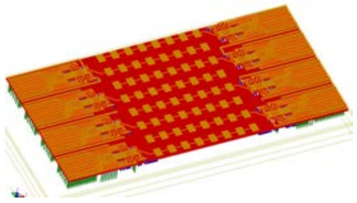
High integration density:
fitting transceiver into $\lambda/2$ pitch
transistor footprint
50Ω line interconnect pitch.

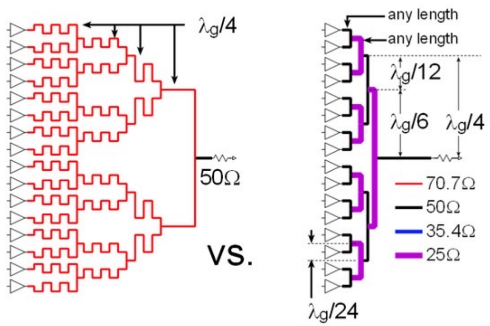
High density for efficient power-combining
short lines = low-loss lines
transistor power cells must be small to fit

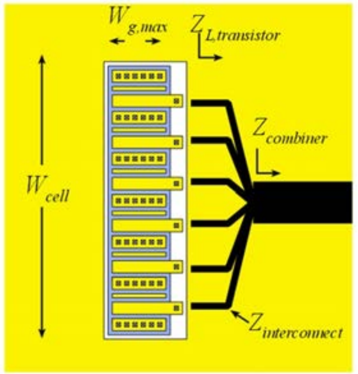
High density for efficient multi-finger transistors
short lines = low-loss lines

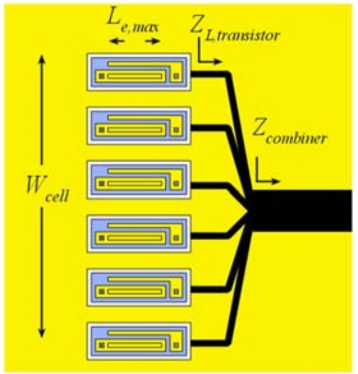




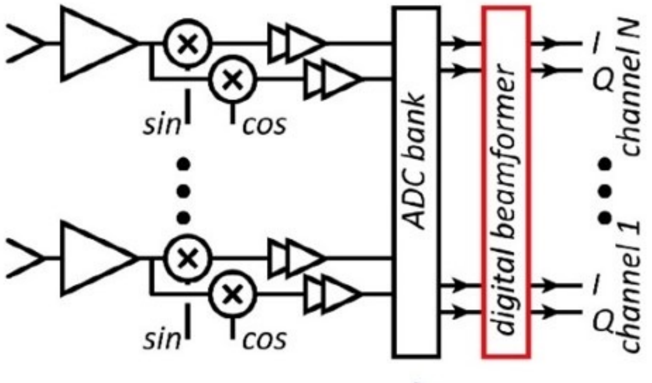








Implications: massive MIMO beamforming



 # channels / # signals is spatial oversampling:

ADCs/DACs: not many bits required
(Madhow, Studer, Rodwell)

RF component linearity: 1dB compression points can be fairly low
(Madhow)

Phase noise: phase nose can be moderately high

Beamspace:
lower frequencies, many NLOS paths, complicated channel matrix: $O(M^3)$ to beamform
higher frequencies, few NLOS paths, simpler channel matrix: FFT, $O(M \cdot \log M)$ to beamform
easier to separate signals in beamspace
fewer bits in signal; fewer bits in FFT coefficients.
(Studer, Madhow)