Future Analog Electronics and Intelligent Sensing
SIA Webinar

SIA-SRC Decadal Plan for Semiconductors

Decadal Plan for Semiconductors - 5 Seismic Shifts

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

https://www.src.org/about/decadal-plan/
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**
“Interface to the Real World”

Research Themes/Opportunities

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

**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”

- $10^9$ light quanta
- $10^7 R^*$ quanta
- $10^5$ glutamate quanta
- Readout Cone quanta
- $10^2$ glutamate quanta
- horizontal cell
  - 4x loss cone terminals
- bipolar terminals
- ganglion cell
  - 2.5x loss cone terminals
- ~1 spike

Photoreceptors

Optic Nerve

Processing Reduction

<table>
<thead>
<tr>
<th>Sensory System</th>
<th>Bits per second</th>
<th>Processed by the brain (bits/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eyes</td>
<td>10,000,000</td>
<td>40</td>
</tr>
<tr>
<td>Ears</td>
<td>100,000</td>
<td>5</td>
</tr>
<tr>
<td>Smell</td>
<td>100,000</td>
<td>1</td>
</tr>
<tr>
<td>Taste</td>
<td>1,000</td>
<td>1</td>
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Ref. “Principles of Neural Design”, Sterling and Laughlin
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.*

![Diagram of Sensing System Approach](image)
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

Roundtable:
• Steven Spurgeon
  Staff Scientist, Energy and Environment Directorate / Pacific Northwest National Laboratory

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

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

• Wai Lee
  Chief Technologist, Sensing Business / Texas Instruments

• 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
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.


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

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
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.

\[ N \propto \frac{L^4}{\lambda^2 R^2} \]

Spatially-multiplexed mm-wave base stations

Spatially-multiplexed mm-wave base stations

\[ \Delta \theta \propto \frac{\lambda}{L} \]
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.
HETEROGENEOUS AND CO-FUNCTIONAL INTEGRATION NEEDS, OPPORTUNITIES, CHALLENGES

SRC Analog Trajectories
Kostas Doris

JUNE 2021
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

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

- 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

**RADAR WAVELENGTH EVOLUTION – EACH STEP ENABLES A WIDER SOLUTION SPACE**

**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

**Much more is needed!**

**RADAR IS EVOLVING TOWARDS COMMUNICATIONS**

- 7D=R,D,t,A,E,d,c → Cognitive Radar
- 6D=R,D,t,A,E,d → Imaging Radar: UWB
- 5D=R,D,t,A,E → Imaging Radar: FCM
- 4.5D=R,D,t,A,E → 3D Radar: FMCW
- 4D=R,D,t,A → FMCW Radar
- 3D=R,D,t → Monopulse Radar

- Time multiplexed MIMO digital beam forming
- MIMO phase coding
- Frequency domain massive MIMO code domain communication
- Adoption to environment distributed sensor
RADAR / SENSING NEEDS AND 77GHZ BAND LIMITATIONS

Interference management needed! Advanced waveforms in conflict with FMCW.

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

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

Mapping, localization, classification

Size reduction

NXP’s 77GHz Multi mode MIMO RADAR

Interference management needed! Advanced waveforms in conflict with FMCW.
IMPROVING RESOLUTION - OPPORTUNITIES AND CHALLENGES

- 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

Massive MIMO

Time, frequency, code

Compressive Sensing

Distributed radar

Radar image Processing with A.I.

Enhanced classification

Explore channel behavior wavelenths

multiple functions, in-package integration, multiple nodes

advanced DSP: all conditioned together to the sensing function!

Mm-wave signal generation

RF CMOS? SiGe?

Efficiency, reliability, Noise

Arbitrary Waveform generators

supporting radar signatures

Synchronization in massive arrays

Full duplex / echo cancellation for MIMO

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

Context/feature extraction in Analog to Digital
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

- 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

Source: Prof. Akin, UTD, SRC Task 2810.016
Compressive Sensing and A2I

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

- 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

Wearable ECG
~10x power reduction by adaptive sampling

Source: Sharma, et al, IEDM 2016
New Trajectories for Analog Electronics

Boris Murmann
June 10, 2021
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
Predistorter spectrum sensing
Hammler, TCAS1 2019

Log gradient imager
Young, JSSC 2019

Sub-Nyquist ultrasound
Spaulding, IUS 2015

RF spectrum sensing
Adams, JSSC 2017

Audio feature extraction
Villamizar, TCAS1 2021

Compressive neural recording
Muratore, TBioCAS 2019

Mixed-signal neural network
Bankman, JSSC 2019

772 1b-TOPS/W
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,

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

<table>
<thead>
<tr>
<th>Proposed scaling law</th>
<th>change</th>
</tr>
</thead>
<tbody>
<tr>
<td>carrier frequency</td>
<td>increase 2:1</td>
</tr>
<tr>
<td>aperture area</td>
<td>keep constant</td>
</tr>
<tr>
<td>total transmit power</td>
<td>keep constant</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Implication</th>
<th>change</th>
</tr>
</thead>
<tbody>
<tr>
<td>capacity (# beams-bit rate per beam)</td>
<td>increases 4:1</td>
</tr>
<tr>
<td>number elements</td>
<td>increases 4:1</td>
</tr>
<tr>
<td>RF power per cm² aperture area</td>
<td>stays constant</td>
</tr>
<tr>
<td>RF power per element</td>
<td>decreases 4:1</td>
</tr>
</tbody>
</table>

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, ΔΦ...) → 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
  50$\Omega$ 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 noise 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)