Semiconductor Research Corporation

CogniSense
CENTER ON COGNITIVE MULTISPECTRAL SENSORS

CogniSense: Center on Cognitive Multispectral Sensors

Center Overview and Highlights

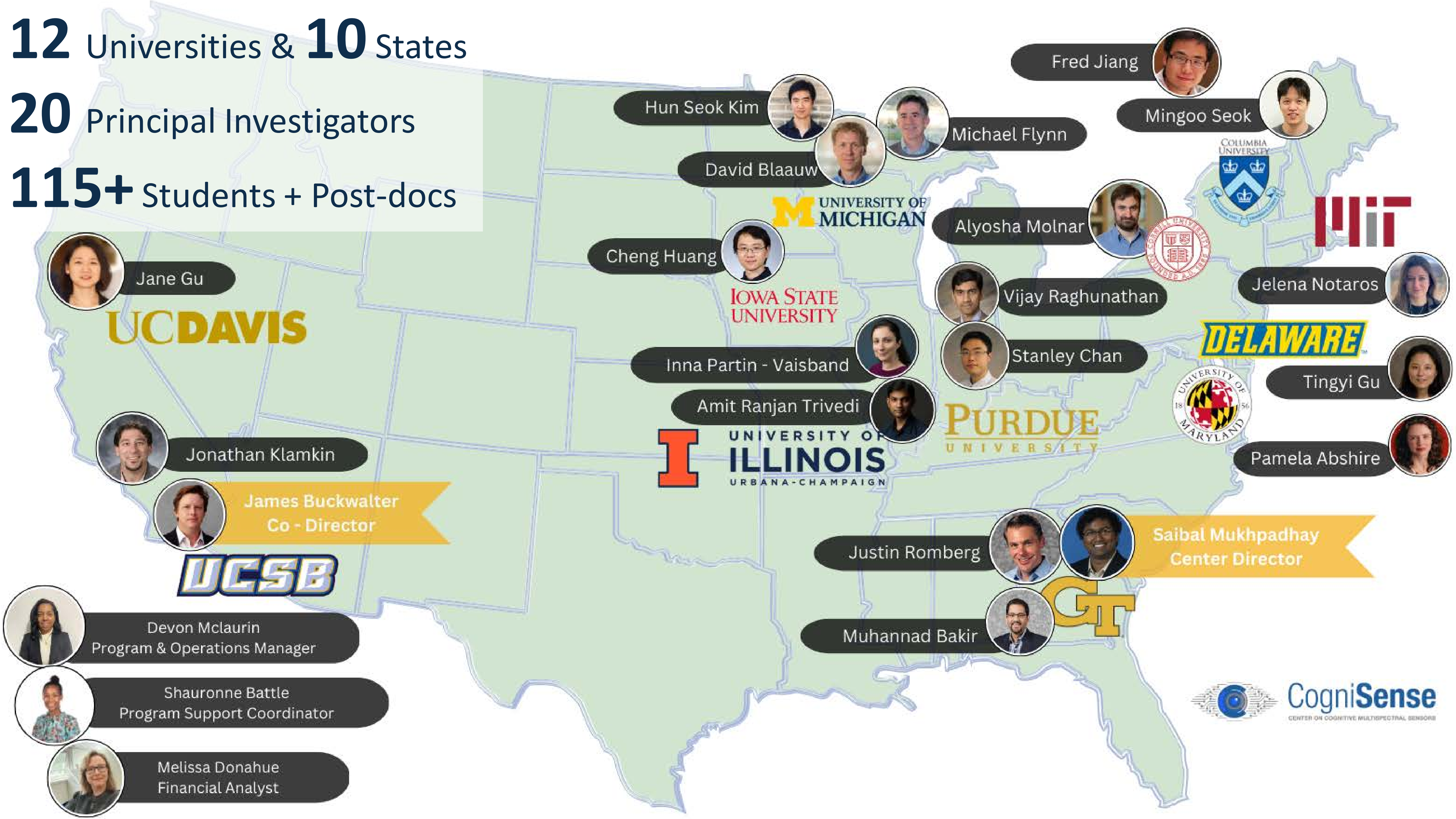
Director: Saibal Mukhopadhyay, Georgia Tech
Co-Director: James Buckwalter, University of California, Santa Barbara

Georgia Institute of Technology, UC Santa Barbara, University of Michigan, University of Illinois Chicago, Columbia University, Purdue University, Cornell University, Massachusetts Institute of Technology, University of Maryland, University of Delaware, University of California, Davis, and Iowa State University,

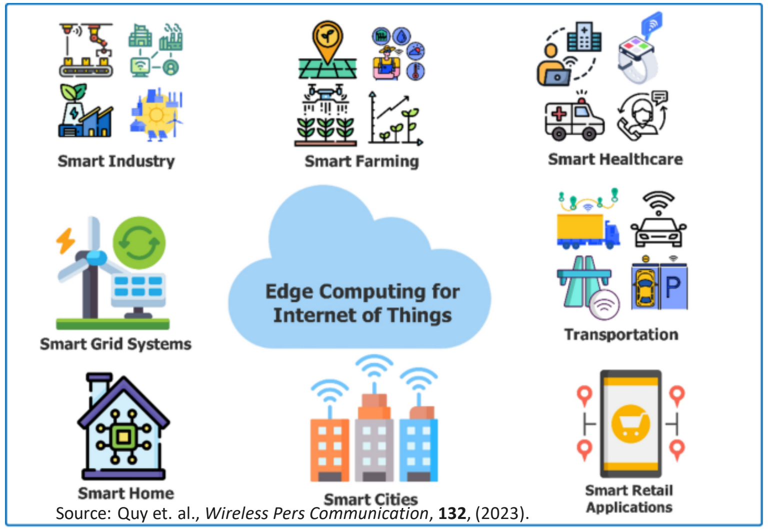
12 Universities & **10** States

20 Principal Investigators

115+ Students + Post-docs



Sensors Drive Intelligent Systems



Source: Quy et. al., *Wireless Pers Communication*, **132**, (2023).

Source: https://www.techaheadcorp.com/blog/future-of-self-driving-cars/

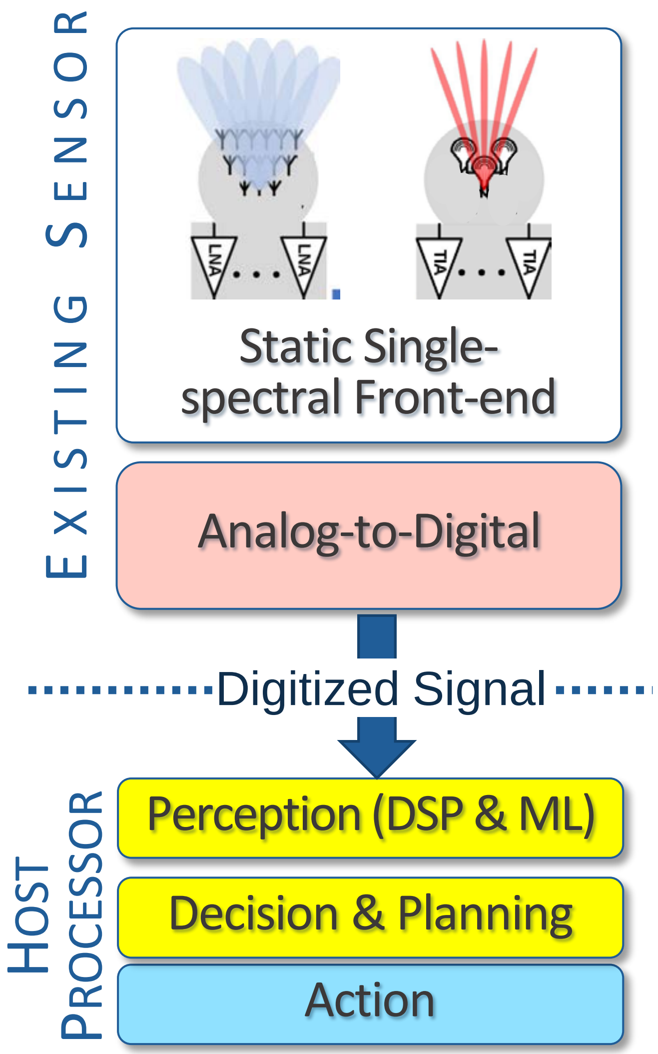
UniTree Robot

Anafi Drone

Source: Image generated using ChatGPT

Unobstructed sensing is critical to deploy autonomous platforms.

Analog Data Deluge: A Key Challenge in Today's Sensors



Wideband and multi-modal pixel arrays can provide high-quality imaging for perception.

Challenge:

- **Analog Data Deluge:** Large volume of digitized data is continuously generated and transmitted from the sensors.
- **Power dissipation can be un-manageable.** Large power dissipation in many ADCs, I/O of the sensors, and downstream computation to process high-volume of sensor data.

Power and data volume may ultimately limit the quality of perception that can be achieved.

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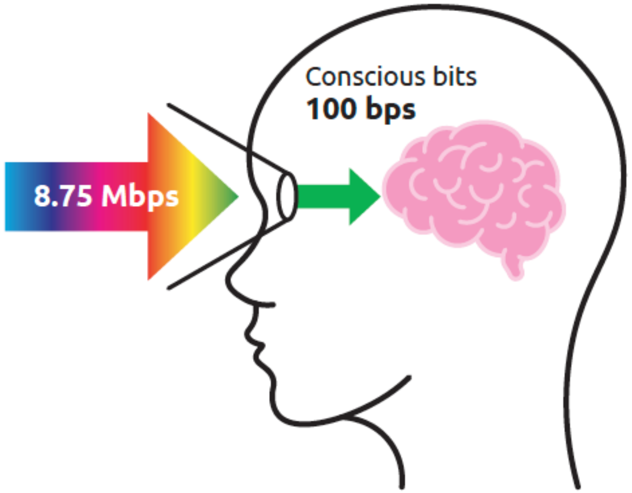
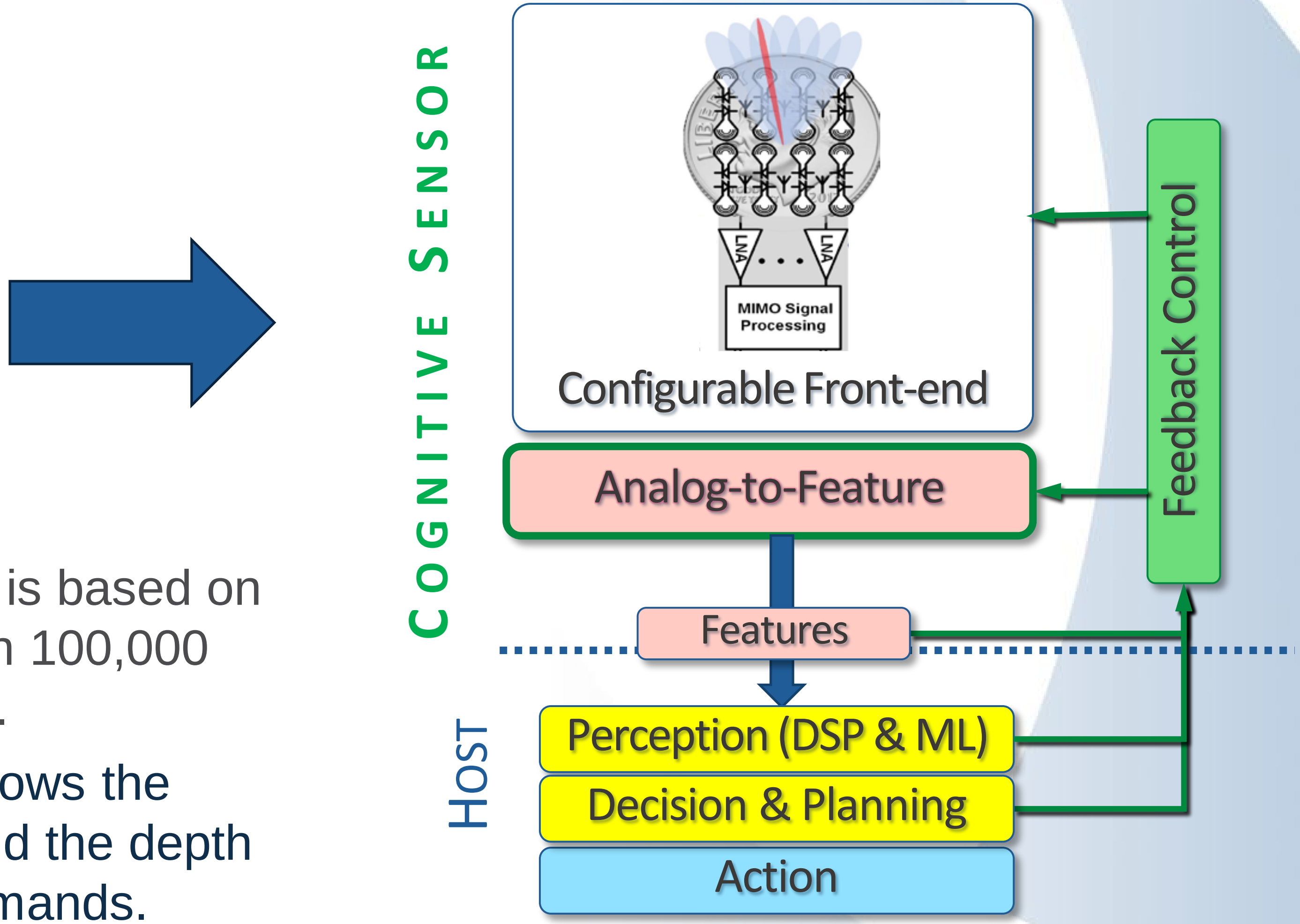
Inspiration from Biology

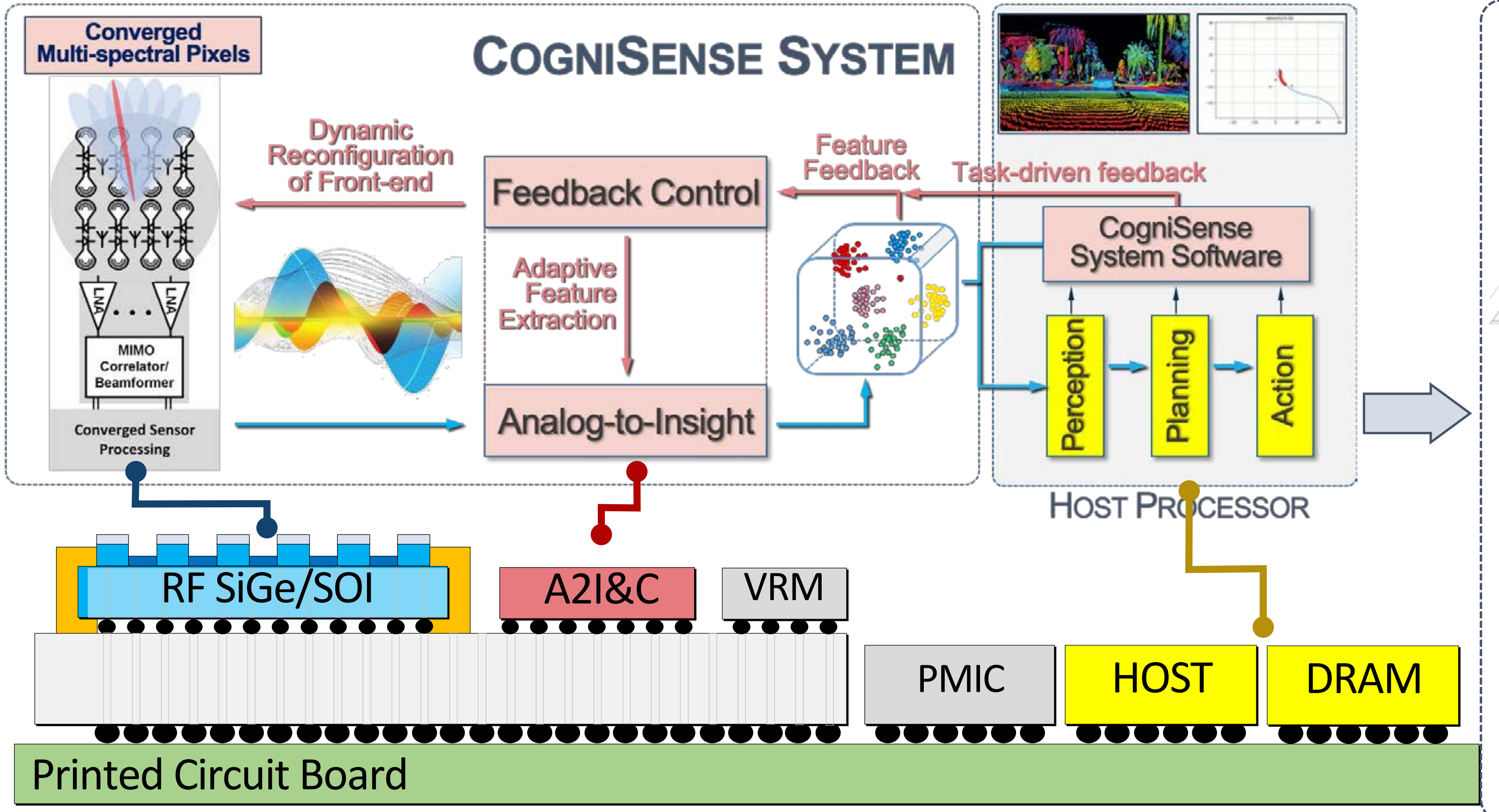




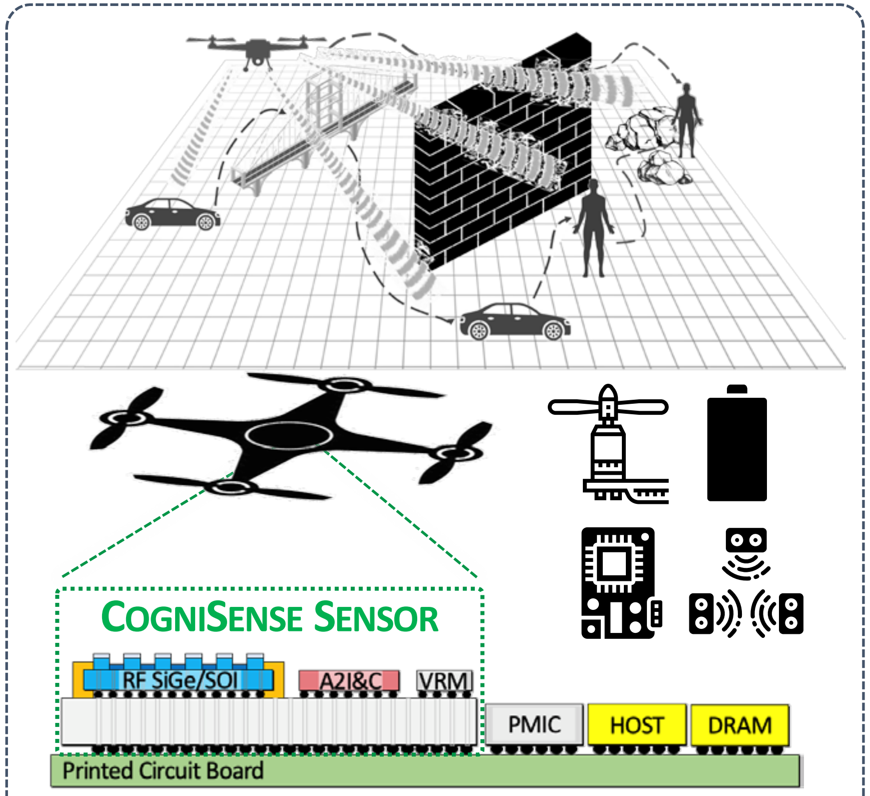
- The brain's ability to perceive and reason is based on ultra compressed sensing capabilities with 100,000 data reduction and a low operation power.
- Closed-loop feedback from the senses allows the brain to adapt the level of engagement and the depth of cognitive processing based on task demands.

Our Vision: Cognitive multi-spectral sensors that dynamically adapt what is being sensed and how sensed signals are processed to real-time changes in the environment.

CogniSense: Technology Overview



CogniSense Applications

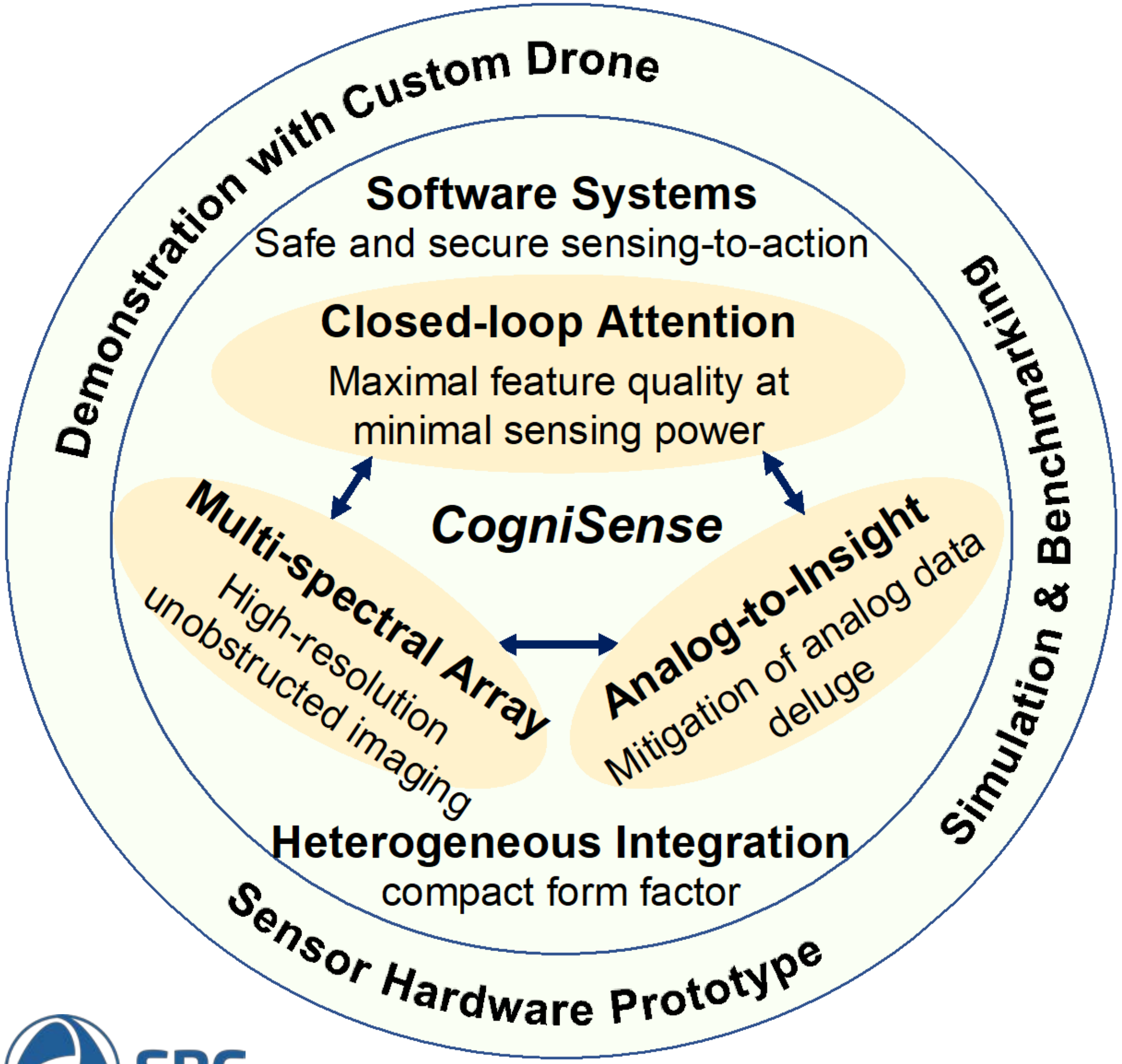


CogniSense Sensor in a System

Custom drone with CogniSense Sensor

Cognitive multi-spectral sensors directly generate trustworthy insights from wideband multi-modal analog signals using closed-loop feedback control of the sensor hardware and feature extraction algorithms that enable energy-efficient sensing-to-action.

Research Vectors



Thrust 1: Multi-spectral Pixel Array
Leaders: **James Buckwalter** & Jelena Notarose

Thrust 2: Analog-to-Insight
Leaders: **Justin Romberg** & Hun-seok Kim

Thrust 3: Closed-loop Attention
Leaders: Mingoo Seok & Alyosha Molnar

Thrust 4: Heterogeneous Integration
Leaders: **Inna Patin-Vaisband**

Thrust 5: System Software & Integration
Leaders: Amit Trivedi & Vijay Raghunathan

Research Highlights from Year 1

Multi-spectral front-end & sensor integration

- Power-efficient 140GHz FMCW radar
- Beam-steering & switched beam Lidar
- High dynamic range passive imaging
- Front-end circuits for sensor convergence
- New power management circuits
- 3D HI (Cu-Cu bonding) optimized for electrical & thermal management in CogniSense sensor.

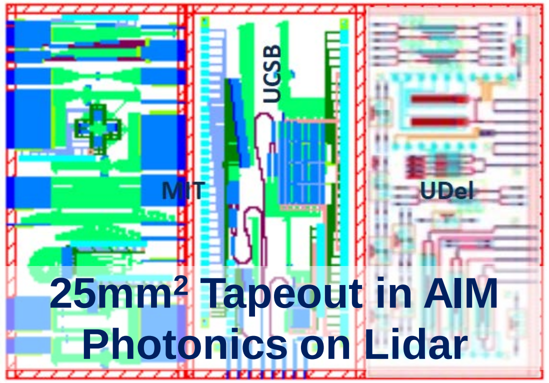
Algorithms & Circuits for feature extraction and processing to reduce analog data

- Linear algorithm to extract features for analog signals.
- Multi-modal feature fusion and processing algorithms
- New compute-in-memory circuits for analog feature extraction, floating point operation, optimization, etc.
- Efficient hardware architecture for neural network.
- Fundamental analysis of sensor trade-offs.

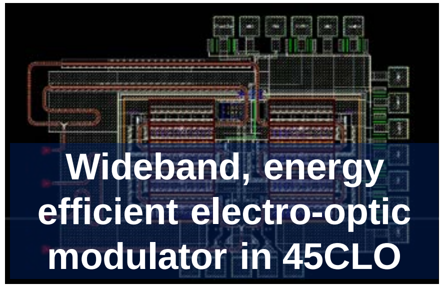
Cross-stack adaptation for power-quality trade-off in CogniSense sensing-to-action

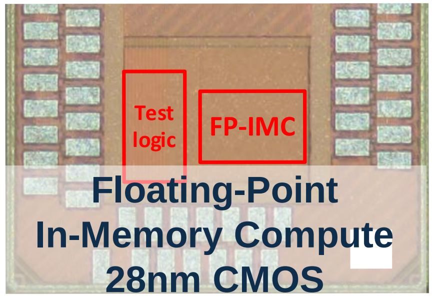
- Uncertainty-aware sensor processing with trust and reputation tracking
- Adaptive on-sensor feature extraction algorithms for analog & multi-modal inputs
- New radar-based perception algorithms and task-dependent sensor control
- Security architecture for CogniSense sensors
- Multi-modal custom drone platform to study CogniSense concepts

Research Highlights from Year 1

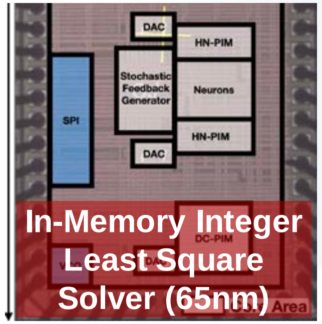


25mm² Tapeout in AIM Photonics on Lidar

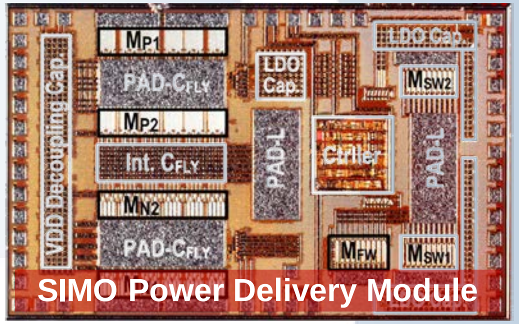

Wideband, energy efficient electro-optic modulator in 45CLO



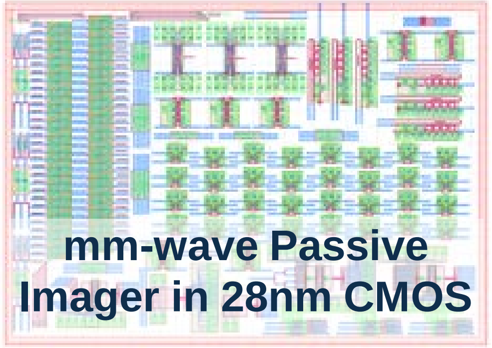
Floating-Point In-Memory Compute 28nm CMOS

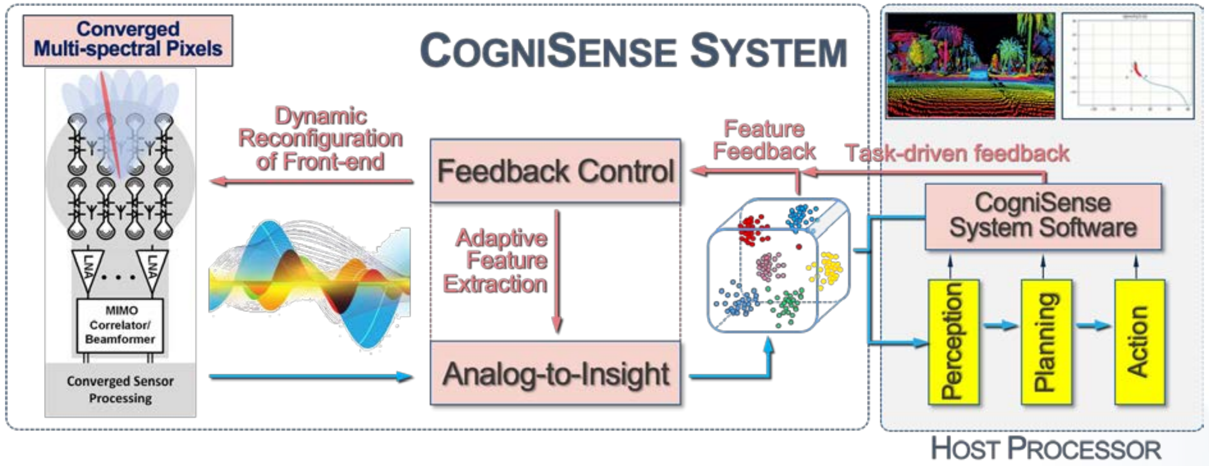


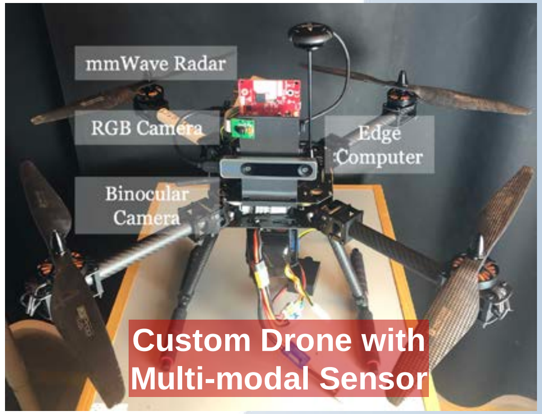
In-Memory Integer Least Square Solver (65nm)



SIMO Power Delivery Module

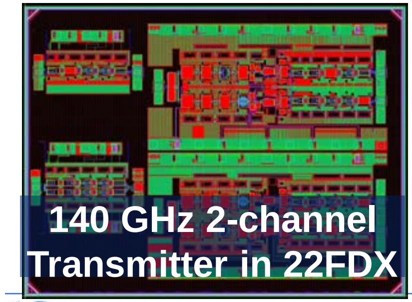

mm-wave Passive Imager in 28nm CMOS

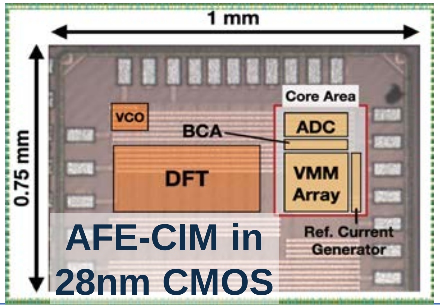




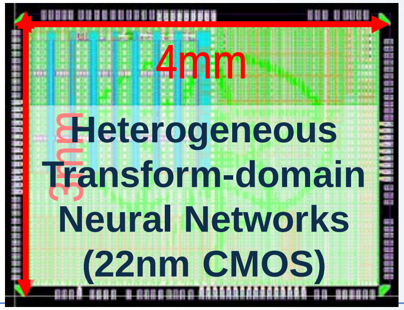
Custom Drone with Multi-modal Sensor

Multi-band (20 and 60 GHz), high dynamic range receiver in Intel 16

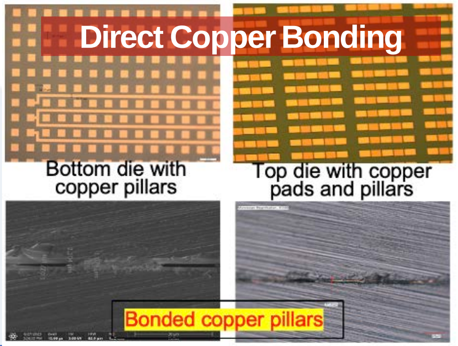

140 GHz 2-channel Transmitter in 22FDX



AFE-CIM in 28nm CMOS



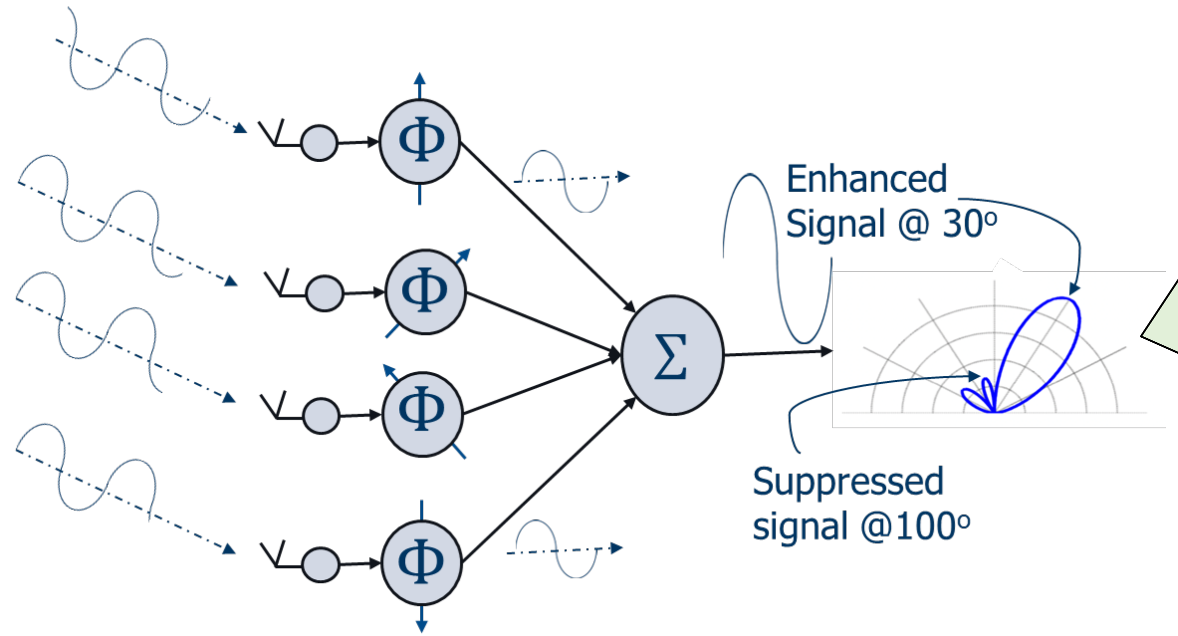
Heterogeneous Transform-domain Neural Networks (22nm CMOS)



Direct Copper Bonding

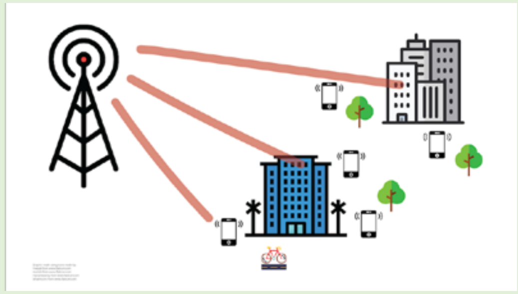
Example of Mitigating Analog Data Deluge with Cognitive Sensing

Beamforming Receiver with Phased Array Sensor

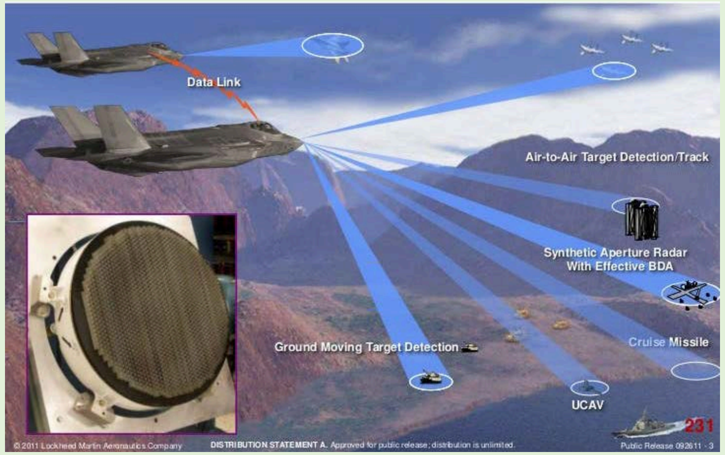


Missile Defense Systems (AN/FPS-115 PAWS Radar)

5G Communications



Aircrafts (AESA Radar in F-35)



Beamforming: Adjust the phase and amplitude of signals from antenna array to generate an output beam.

- Directional Selectivity
- Suppressed Interference/noise
- Improves SNR

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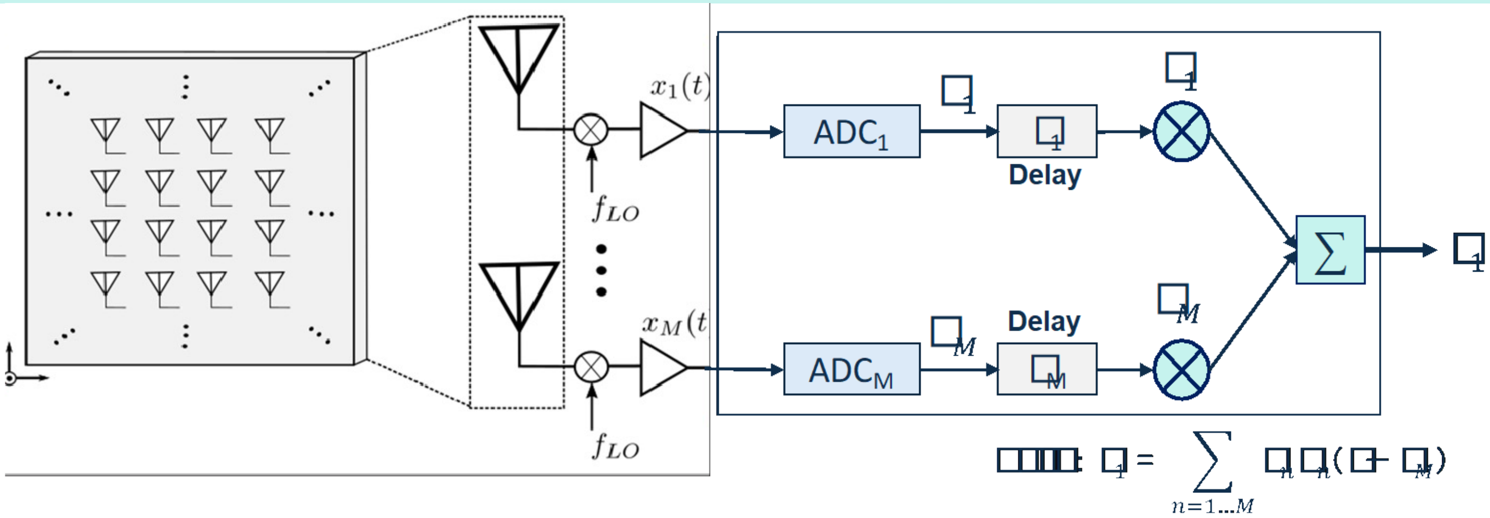
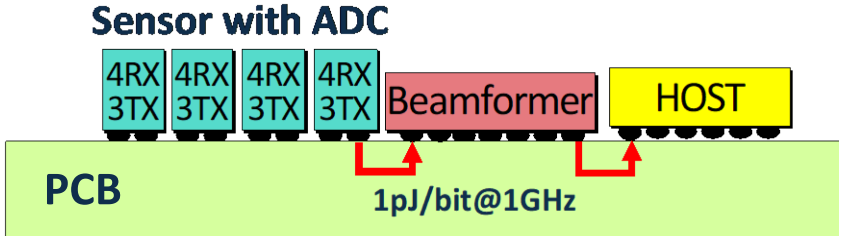
Example of Mitigating Analog Data Deluge with Cognitive Sensing

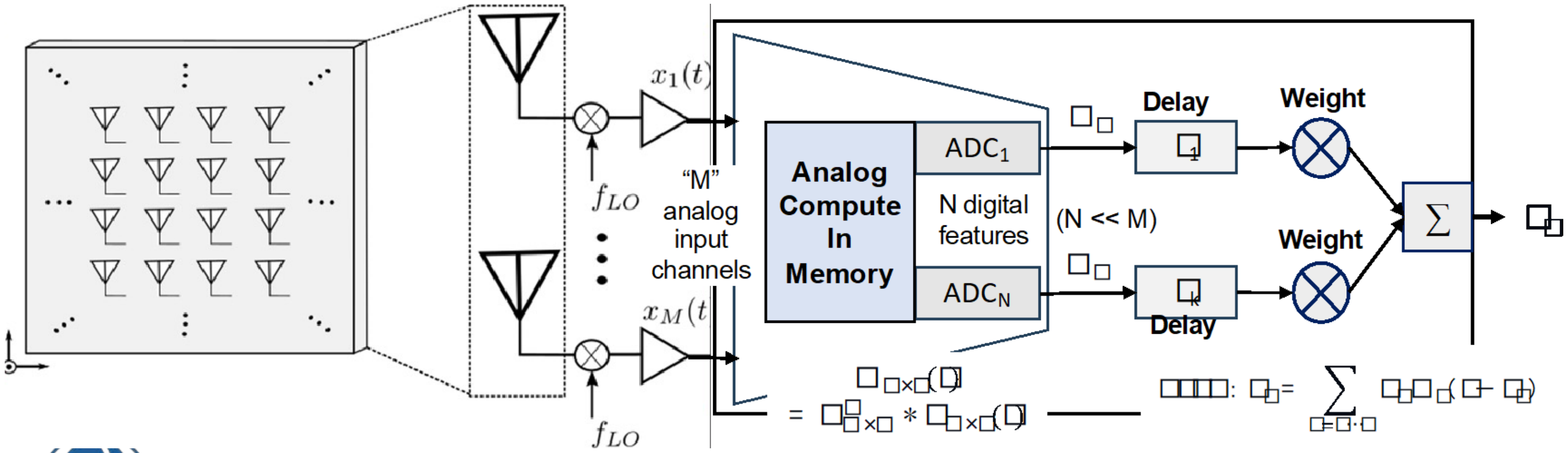
Baseline: A True-Time Delay based Digital Beamformer

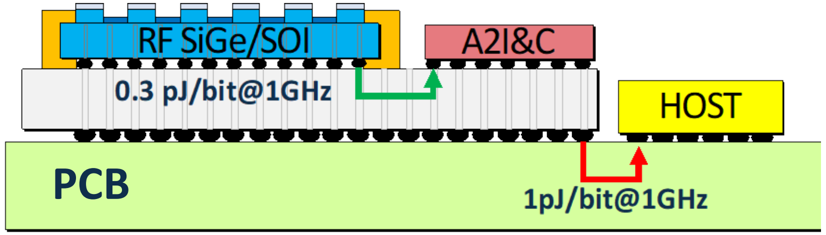




Digitization of wideband analog signals leads to high power dissipation in data converters and digital computation.

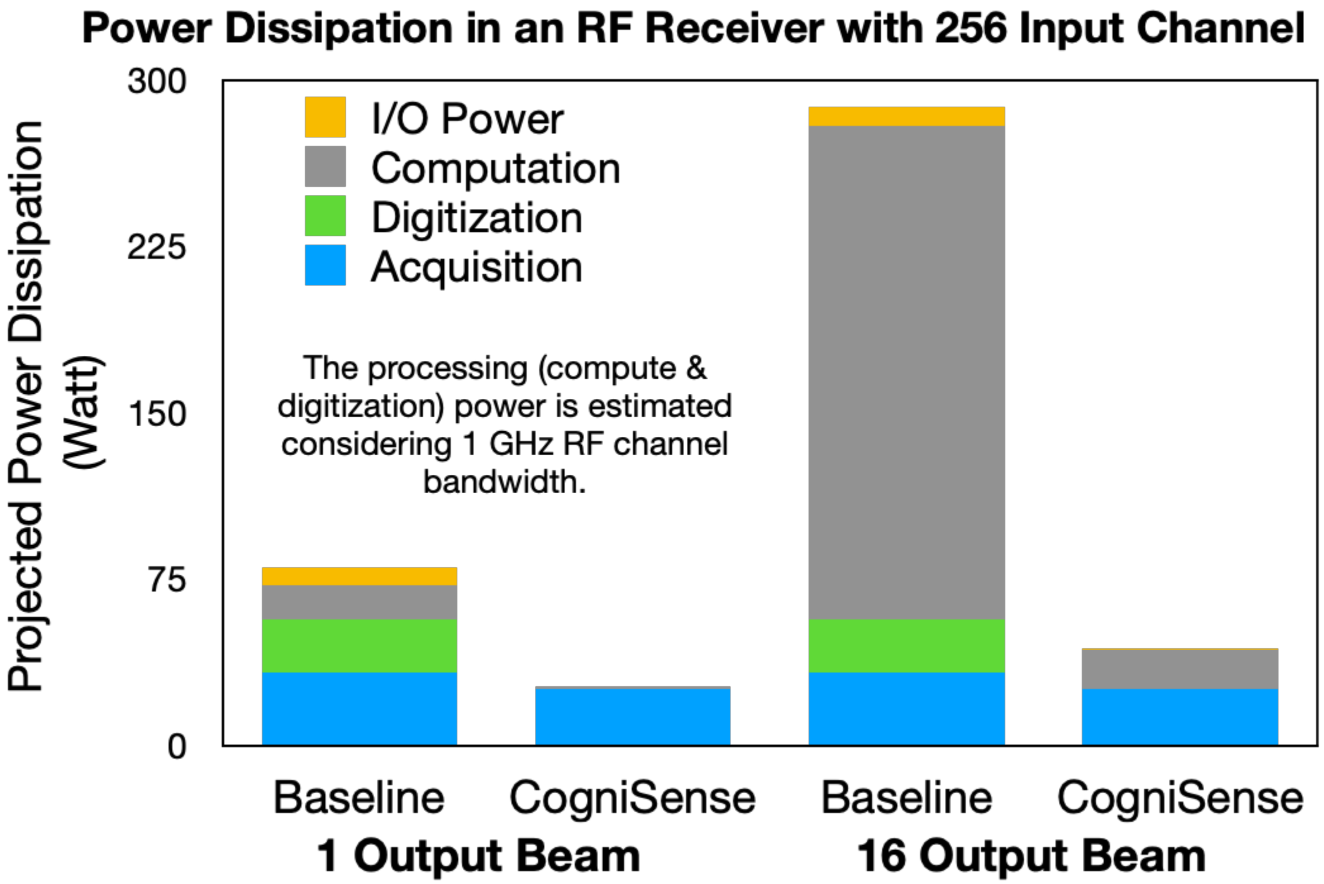
CogniSense: Beamformer with Linear Embedding





Analog feature extraction in CogniSense reduces digitization and computation power.

Example of Mitigating Analog Data Deluge with Cognitive Sensing



CogniSense Innovations & Tasks
• Beamforming with linear feature extraction & digital feature processing [2.1]
• Analog compute-in-memory circuit for linear feature extraction from analog signals [2.2]
• Power-efficient RF receiver front-end (~100mW/channel) [1.1]
• Integration of sensors and compute in an interposer reduces I/O power [4.3]

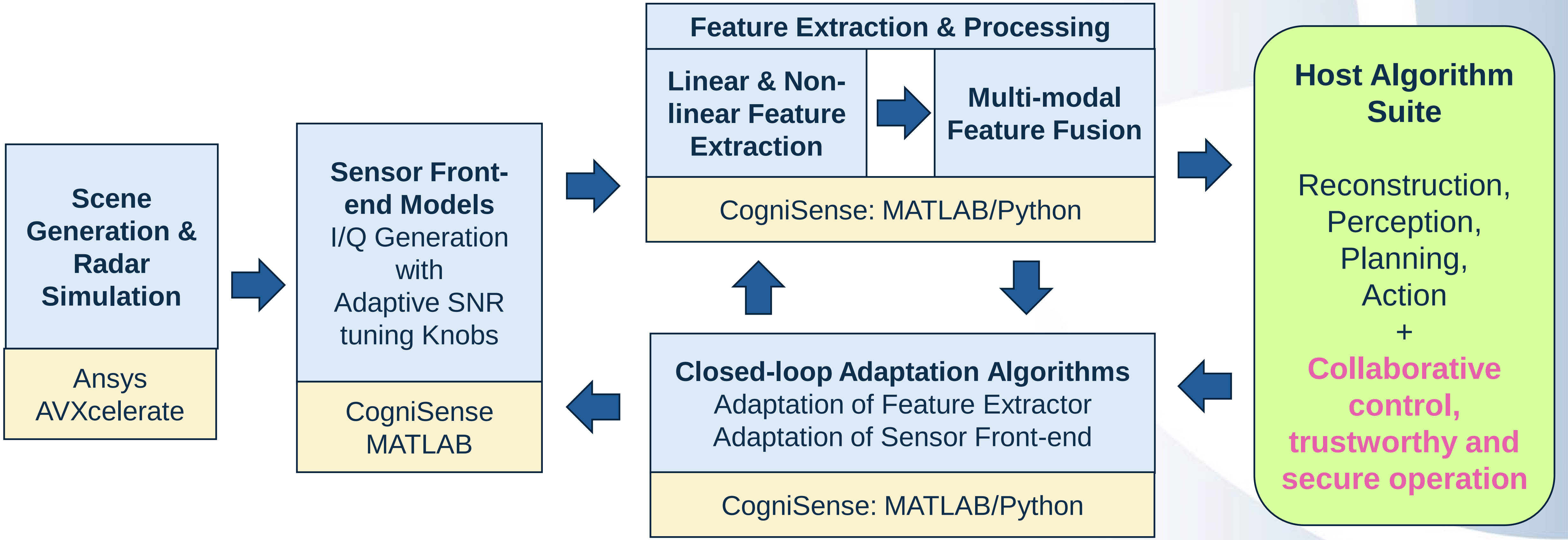
Potential Impact

- CogniSense sensor need 6.5X less power than the baseline for 16 beams.
- One can form > 200 beams with the power needed for 16 beams in the baseline.

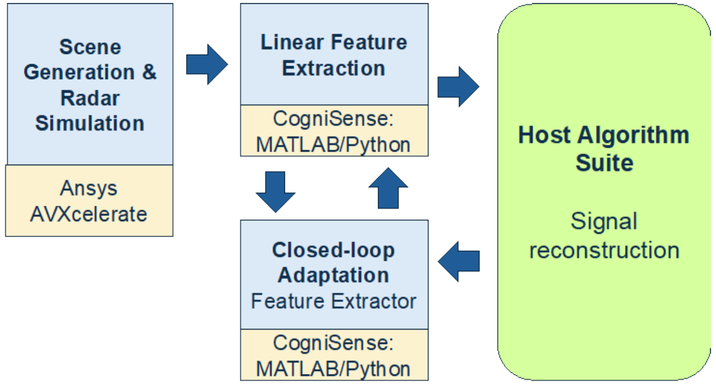
Key Plans of Actions in Year 2

- **End-to-end simulation environment**
  - Radar and lidar-based input simulation
  - Integrated software pipeline coupling algorithmic innovations across center
  - Power/performance models to couple design innovations
- **System adaptation & sensing-to-action**
  - Define challenge application for case studies
  - Emphasize system & software challenges like security
- **Metrics & Benchmarking**
  - Establish thrust level metrics for sensing quality, analog data deluge, and adaptive power efficiency
  - Evaluate progress of each component, sub-system, and sensing-to-action against metrics.

Key Plan of Action: Sensor Simulation Platform

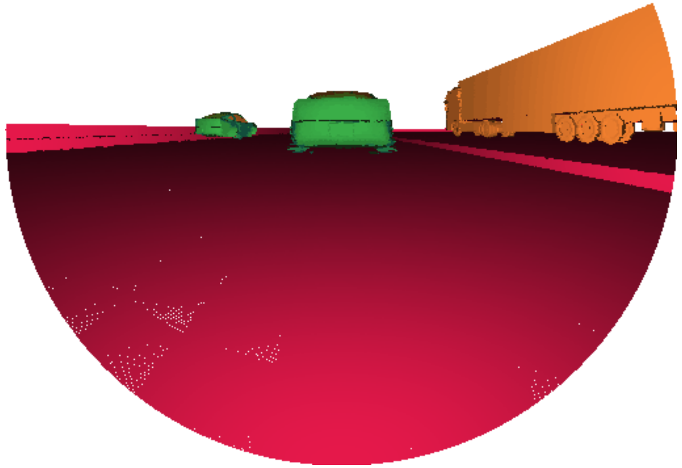


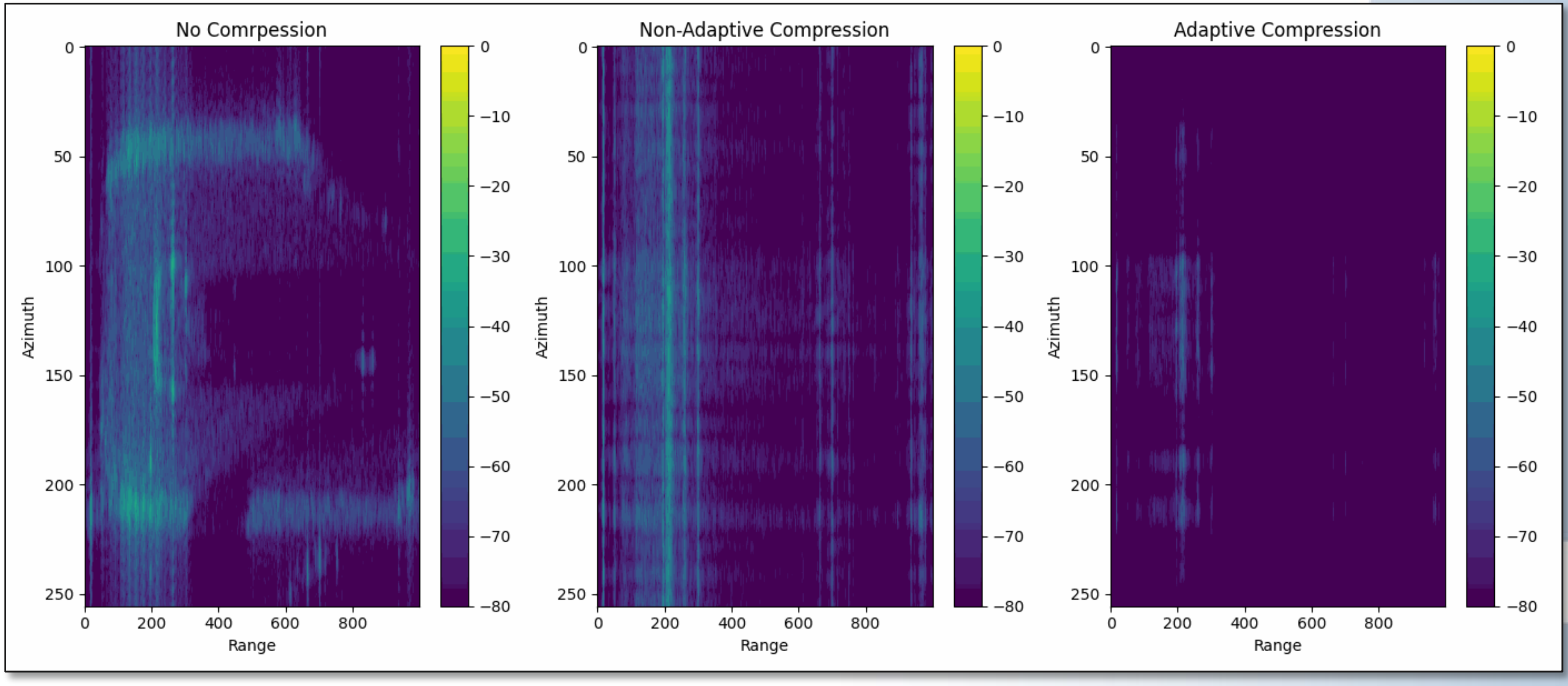
Sensor Modeling Platform: Scene to Feature



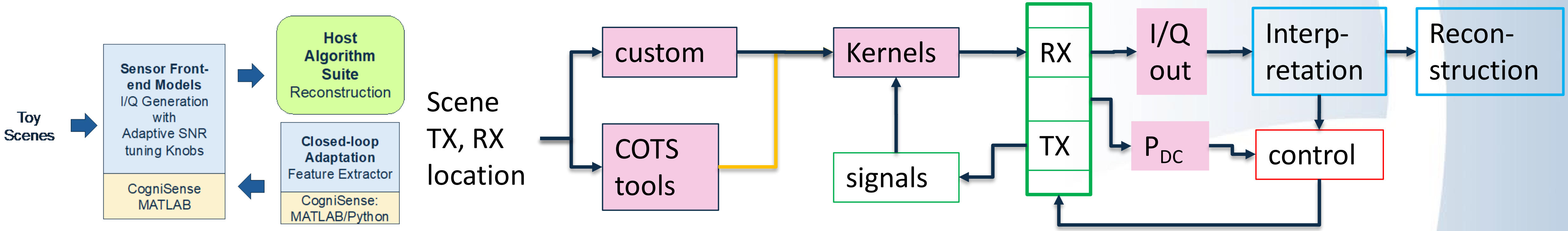
Closed-loop simulation with adaptive feature extraction:

- Front end: Ansys AVXelerate simulates 32x32 array @ 10 GHz BW
- 1024:16 (64x) compression using linear feature extraction
- Adaptive feature selection w/ update rate 1 kHz

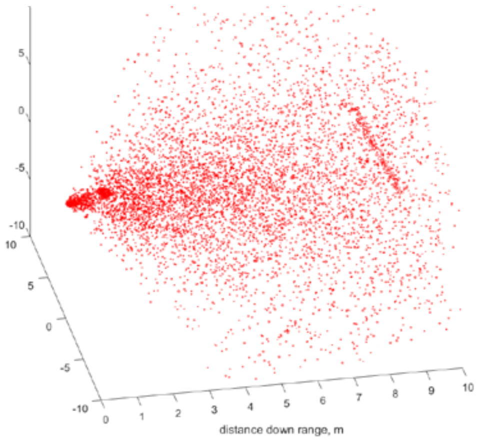




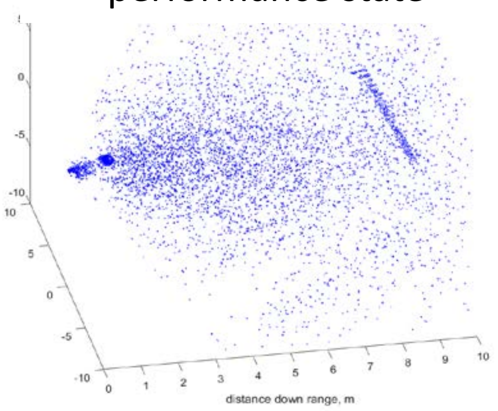
Sensor Modeling Platform: Effect of Sensor Hardware on Feature



All RX in a low power state

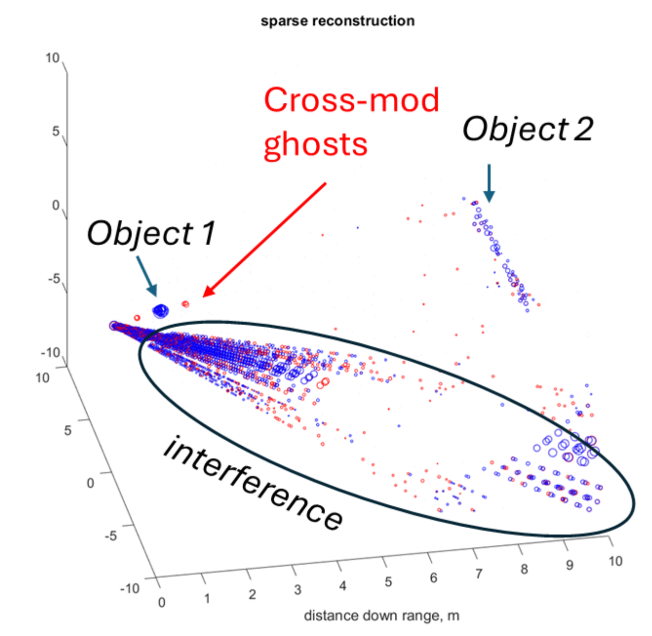


All RX in a higher performance state



AM-modulated Interference generates ghosts

higher linearity removes ghosts
Red: low power/linearity mode
Blue: higher power, better linearity



Key Plan of Action: System Hardware Modeling Platform

Power Performance Models for Sensor Modalities

FMCW Radar and Lidar
Adaptive Power Management
(Thrust 1)

Link Models in Target HI Technologies

Signal Loss, Power Dissipation, Cross-talk, Bandwidth
(Thrust 4)

Power & Performance Models for Baseband Processing

Hardware accelerator models for feature extraction & on-line adaptation
(Thrust 2 & 3)

CogniSense System Simulation & Design Space Exploration Tools

Thermal Models for HI Technology

Materials, Cooling technology
(Thrust 4)

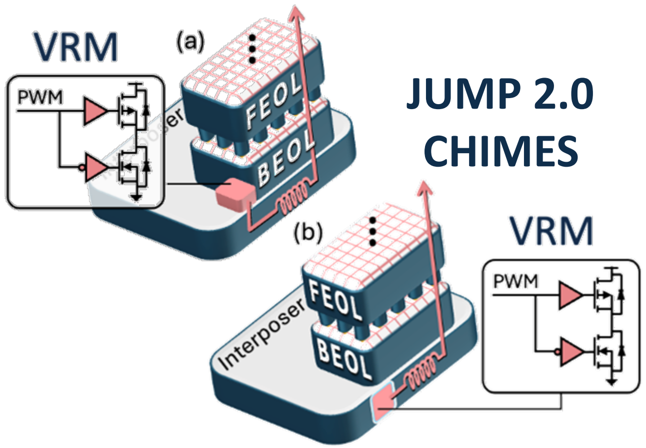
System Design & Integration

HI Technology, Chiplet placements & routing options
(Thrust 1 & 4)

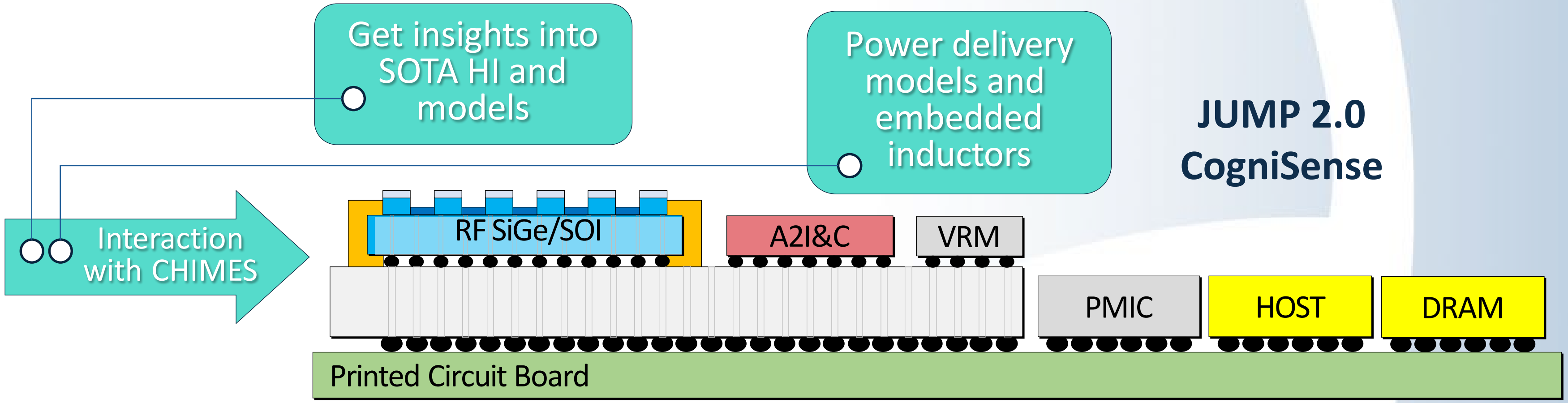
CogniSense Power Delivery Models

Inductor & capacitor, Interconnects
Power loss, Power quality
(Thrust 1 & 4)

System Hardware Modeling Plans



JUMP 2.0
CHIMES



JUMP 2.0
CogniSense

3DHI for Radar/LiDAR Integration and Simulation

Approach:

- Reconstituted SiO2 tier (CHIMES technology)
- Encapsulate fabricated chiplets (AIM and GF photonics/RF processes) in oxide
- Exploit through oxide vias and RDL traces on the oxide for rewiring
- Direct copper bonding to simultaneously connect electrical and thermal I/Os

Performance target: Acceptable junction temperature for a given power dissipation

Performance evaluation:

- Simulate performance of thermal Cu bridge, Cu-Cu bonds, and heatsink bonding interface
- Simulate and model the heat flow from the chip to the package

Testbed:

- Passive, glass package stack (collaboration with prof. Buckwalter)
- Electrical characterization of the package, framework for passives and RFIC verification

Power Management Driven Package

Approach:

- Convert power with on-interposer VRM
- Stack advanced (28/16 nm) LV core devices with hybrid topology
- Utilize small, high-quality (L/R) interposer-embedded inductors

Challenges and proposed solutions:

- Get access to GF 22FDX
- Transition to 22 nm and higher frequency VRMs
- Utilize commercial small-form-factor integratable on Si interposers power inductors (e.g., 0402)

Key Plan of Action: Demonstration & Benchmarking

Algorithm Suite from Thrust-V for collaborative control, trustworthy and secure operation

- ChirpNet
- STARNet
- Conformal
- CLUE
- Security Coproc.

NVIDIA Jetson

Intel Meteor Lake

Backend hardware

Algorithms & Hardware Models of CogniSense Sensor (Thrust 1 to 4)

Simulation Environment for Grand Challenge Problem

- Sensor Failure Models
- Sensor Power-Noise Models
- Sensor Attack Models

Models of Non-idealities

On-going Discussions with Sponsors on Potential Approaches for Demonstration of CogniSense Concepts

Custom Drone developed in CogniSense

COTS Platform Available at Georgia Tech

Anafi Drone

UniTree Robot

Boston Dynamics Spot

Key Plan of Action: Grand Challenge Application

Enable Search and Rescue Operations

- Applications in civilian and military space.
- Multi-modal sensing is critical
  - mmWave Radar: see through obstacles; detect motion and materials;
  - Lidar: Enable 3D Vision; detect objects
  - Passive Imaging: Operate in smoke/fire
- Low-power is necessary for longer operation
- Closed-loop attention benefits operation in a dynamic environment.
- Application can be scaled to multiple platforms, each with multiple CogniSense sensors, to connect various innovations pursued within JUMP2.0.
- **Feedback and guidance from members.**

Needs (More) Attention in Year 2

Center	Potential Topic of Interactions
COCOSYS Georgia Tech	Leverage prior experiences of CBRIC and COCOSYS centers on drone platforms and new AI/ML models
CUbiC Columbia	Joint work on photonics, optimizing signal processing pipelines, and exploring joint communication and sensing
ACE UIUC	Security aspects associated with distributed computing and sensing that are relevant to CogniSense
PRISM UCSD	Impact of new memory technology in design of feature extraction algorithms and exploring memory solutions for streaming sensor data.
CHIMES Penn State	Coordination of 3D-HI activities with CHIMES and incorporate new heterogeneous integration and advanced cooling solutions explored in CHIMES into the CogniSense platform.

Example: Cross-Center Collaborations

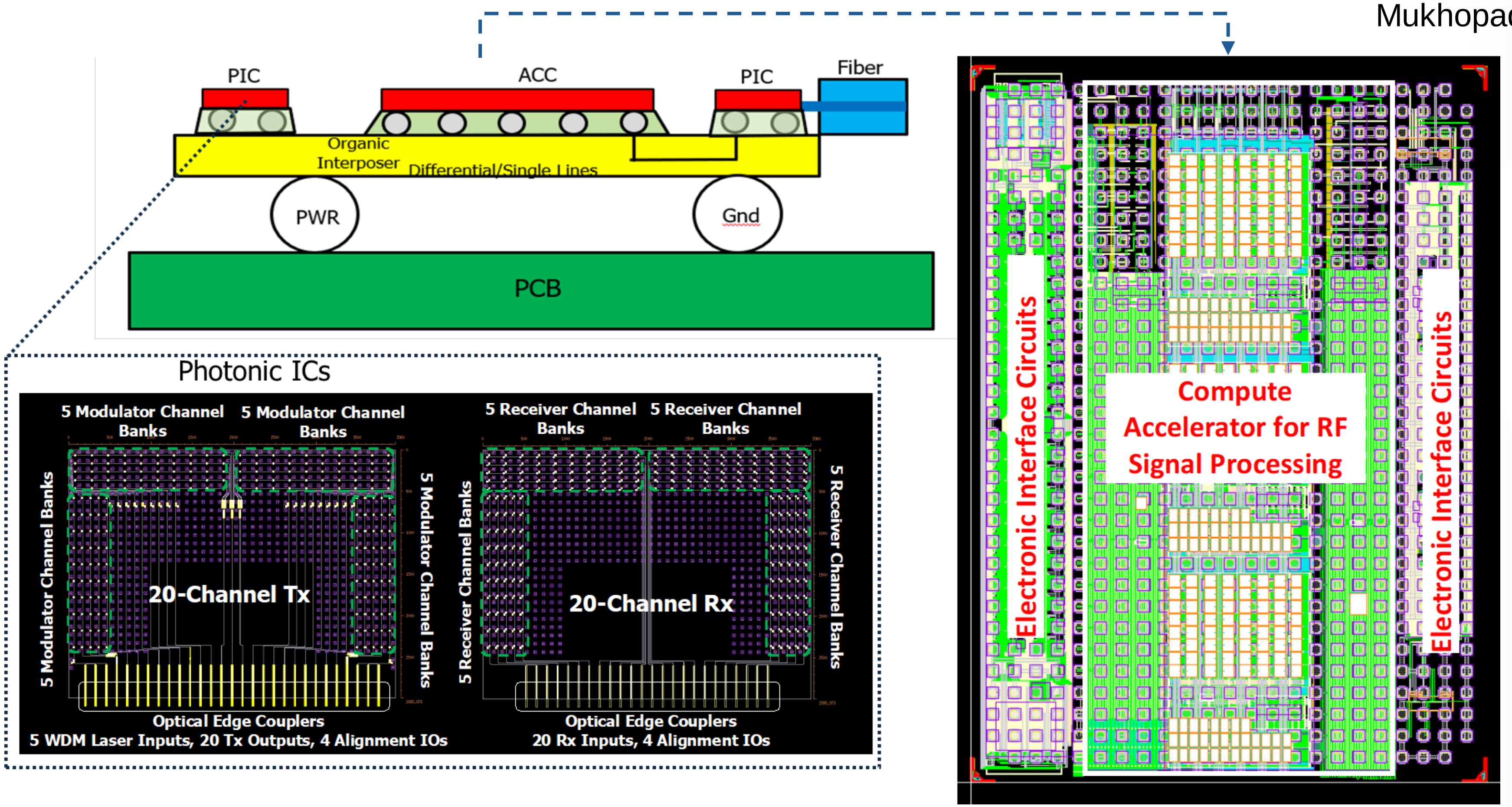
COGNISENSE – CUbiC

Photonic ASIC Integrated Accelerator

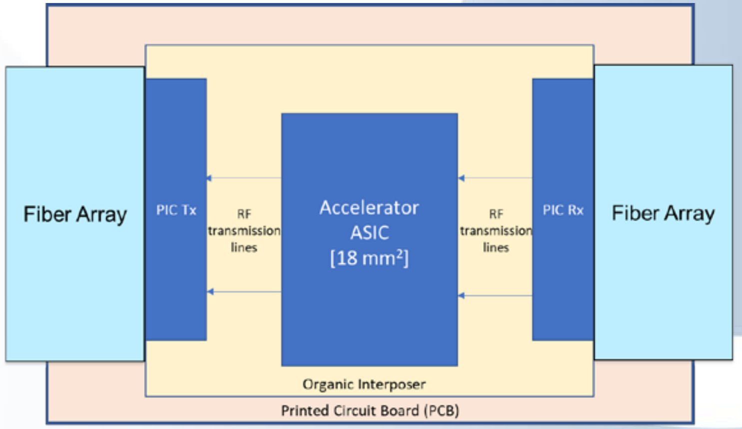
Mukhopadhyay

Seok

Bergman



- Partner with Cubic for demonstration of a HI platform with co-integration of high-speed accelerator ASIC with PIC IO
- Building on DARPA DRBE collaboration
  - PM John Davies
  - Mukhopadhyay, Romberg, Bergman
  - Seok, Swaminathan, Krishna
  - Carloni, Pande



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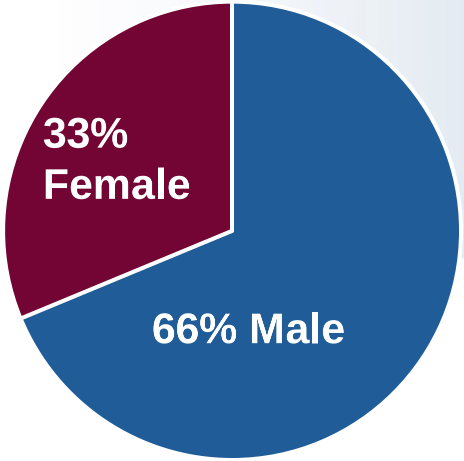
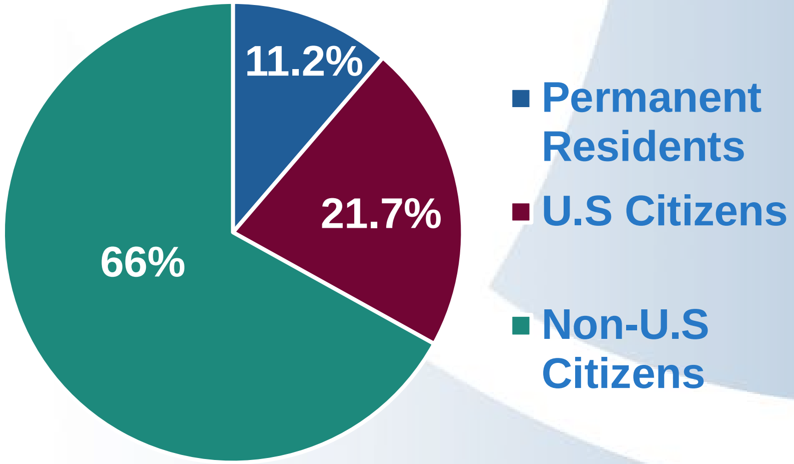
Student Participation

- **Student participation**
  - 115 students/post-docs:
    - Primarily Graduate students (PHD and Masters)
    - Few Undergraduate Students (~5)
  - 50+ students in the Annual Review
- **Student-led publications**
  - **11** students participated in TECHCON2023
  - **40+** Students papers
- **CogniSense student in Members (2023)**
  - **6+** Students joined **SRC Members**
  - **4+** student interned in **SRC Members**





Plan of Action: Broadening Student Participation

- **Our Pledge:** "Strengthen the connection between undergraduate students and industries. Crafting the individual specific career track for undergraduate, graduate, and postdocs."
- **BP Champions:** Prof. Tingyi Gu and Ms. Devon McLaurin

Priorities for Year 2

- **Promoting Diversity & Inclusion**
  - Invite undergraduate students from Georgia Tech, the University of Delaware, and other partnered Universities to participate in annual reviews and upcoming programs.
  - Funds to support their involvement, encouraging valuable contributions and commitment to our goals.
- **Enhancing Educational Experiences:**
  - Fund summer programs at Georgia Tech the University of Delaware and other partnered Universities.
  - Provide hands-on learning, exposure to new concepts, and networking opportunities for student growth.
- **Supporting Inclusivity & Diversity**
  - Invest in undergraduate student participation and summer programs.
  - Strengthen commitment to inclusivity and diversity in our organizations.

Summary

- **What are we trying to do?**
  - Develop energy-efficient and trustworthy multi-spectral sensors for autonomy
- **How it's done today? What are the limitations?**
  - Sensing quality is improved via large and wideband pixel arrays; one array for each modality.
  - Continuous sensing and digitization of all pixels in a wideband pixel array leads to large volume of digitized data (Analog Data Deluge) and high sensing/digitization power.
  - Different sensors for each modality leads to higher sensing power and system cost.
- **What's new in our approach?**
  - Our ***cognitive*** multi-spectral sensors with pixel-level convergence will directly generate trustworthy insights from wideband multi-modal analog signals using closed-loop feedback control of the sensor hardware and feature extraction algorithms.
- **What if we are successful?**
  - Multi-modal sensing arrays that eliminate corner-case obstructions in machine perception and more efficiently use resources (data bandwidth and power).
  - New research direction in designing "adaptive sensors" that learns to traverse the quality versus resource space in evolving environment.

CogniSense

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