Future of RF Spectral Use

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Arizona State University

Director of WISCA Center

Wireless Information Systems and Computational Architectures

Center for Wireless Information Systems and Computational Architectures

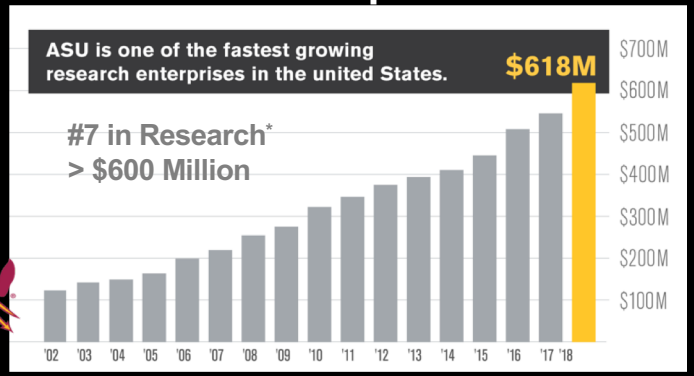
WISCA

Est. June 6, 2016

Arizona State University

- **Largest U.S. University > 100,000 students**
  - Established 1885
- **Reinventing itself to be a dominant research university**
- **Largest U.S. Engineering School**
  - $115 M External Research
  - 24,500 students, ~350 Faculty
- **Electrical, Computer, & Energy Engineering**
  - $32 M in External Research
  - ~70 Faculty (EE)
  - Students: 315 PhD, 650 MS, 2200 Undergrads

Research Expenditures



*U.S. Universities without medical schools









My History

Arizona State University

Bachelor of Science
Electrical Engineering
1989

MOTOROLA

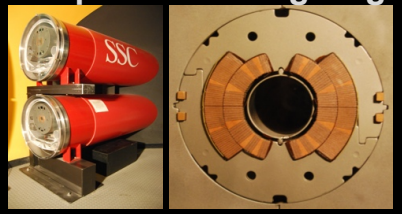
Radio System Support
During Undergrad

GENERAL DYNAMICS

1989-1993

Rocket Avionics

SSC Superconducting Magnets



http://americanhistory.si.edu/collections/search/object/nmah_1452617

LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

1997-2012

Arizona State University

Electrical Engineering
2013

UC San Diego

MS and PhD Physics, 1995 & 1997

CORNELL UNIVERSITY
FOUNDED A.D. 1865

WISCA

ASU's WISCA Center

Wireless Information Systems and Computational Architectures

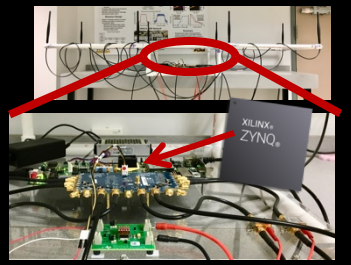
$$\mathbf{Z} \in \mathbb{C}^{(n_{ant} \cdot n_{tap}) \times n_{samp}}$$

$$\mathbf{w} = (\underbrace{\mathbf{Z}\mathbf{Z}^H}_{\hat{\mathbf{C}}})^{-1} \underbrace{\mathbf{Z}\,\underline{\mathbf{s}}_m^H}_{\underline{\mathbf{v}}_m} \in \mathbb{C}^{(n_{ant} \cdot n_{tap}) \times 1}$$

Center for Wireless Information Systems and Computational Architectures
WISCA
Est. June 6, 2016

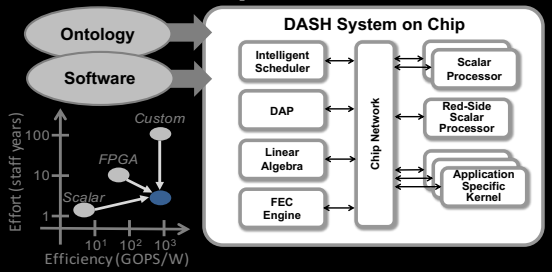
- **Move from new concept, to new theory, to new algorithms, to implementation**
  - Advanced communications, radar, sensing, positioning and navigation
- **Enable next generation advanced RF system research**
- **Perform experimental demonstrations**
- **Develop new high-performance flexible computational architectures**
  - Heterogeneous architectures

SDR Flexible Network



Semi-Custom SDRs

New Chip Architectures



Recent and Current Funding Sources

DARPA · Office of Naval Research ONR Science & Technology · Raytheon · Google · Viasat · NSF · AFOSR Air Force Office of Scientific Research · STT Systems & Technology Research · AIRBUS · NOKIA · Lincoln Laboratory Massachusetts Institute of Technology · *Interstate Broadcasting, LLC*

Topics

- Introduction
- Underlying Tech Development
- Important Developing Areas

How Will RF Systems Change?

Needs

- **Support wider range of users types and needs**
  - Humans have a narrow range of needs
- **Increase node's real-time flexibility**
  - Efficiently support several orders of magnitude of computational rates
- **Support more sophisticated and collaborative use of spectrum**
  - Why do we isolate functions spectrally?

Nonhuman User Dominance

- **Address needs of nonhuman users**
  - Nonhuman radios dominate in terms of number of users
- **Require larger performance dynamic range**
  - Much wider range of communications needs
    - Heartbeat signaling
    - Relay multidimensional video
  - Much wider computational range
    - Measure temperature
    - Reconstruct 3D model from image library
- **May require much lower C-SWaP**
  - Attritable systems
  - Years on a given charge

Internet Toaster

Why? Really… Why?

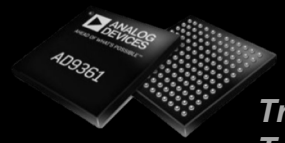
Topics

- Introduction
- **Underlying Tech Development**
- Important Developing Areas

Implications of Commercial Forces

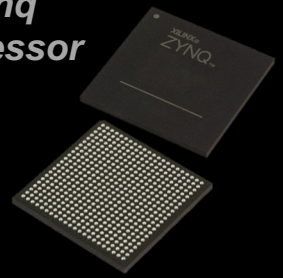
- **Accelerate research with interesting low-cost tools**
  - Broad availability of flexible RF
  - New flexible computational tools

Ettus X310



AD RF Transceiver Technology

Zynq Processor



RFSoC

- **Exploit grab-bag of new 5G tech**
  - Carrier aggregation
  - mmWave
  - Massive MIMO
  - Small cells
  - IoT (narrowband OFDM and non-orthogonal RSMA)

Samsung mmWave 128 Antenna System

https://www.technologyreview.com/s/515631/samsung-says-new-superfast-5g-works-with-handsets-in-motion/

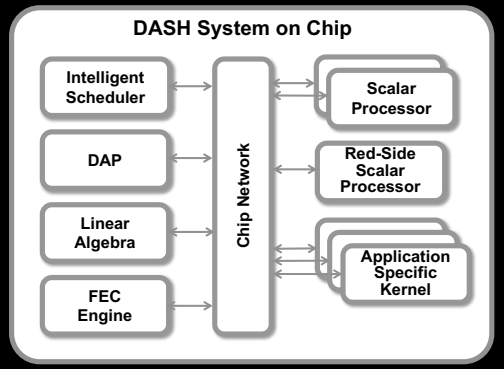
5G

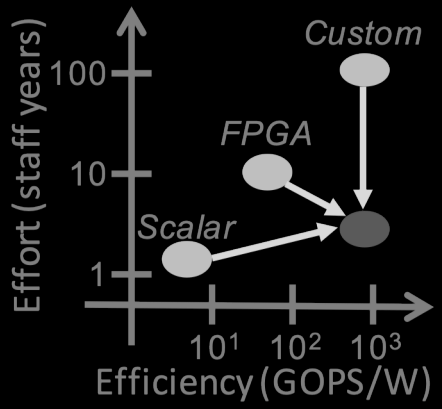
Or, Just Slap a New Sticker on the Phone

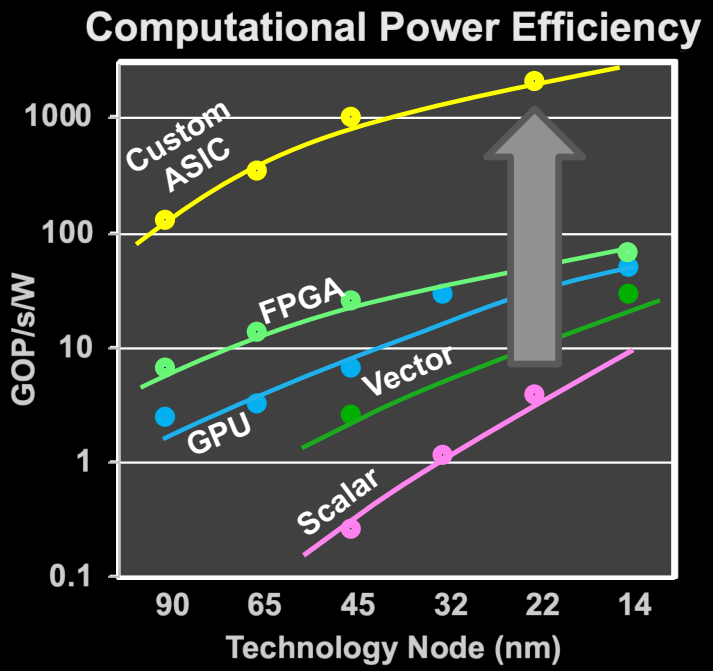
Fixing Processor Technology

DARPA DSSoC DASH Program

- **Break traditional trade between flexibility and performance**
- **Lead DARPA processor program**
  - **Domain-Specific System-on-Chip**
  - **$19M**







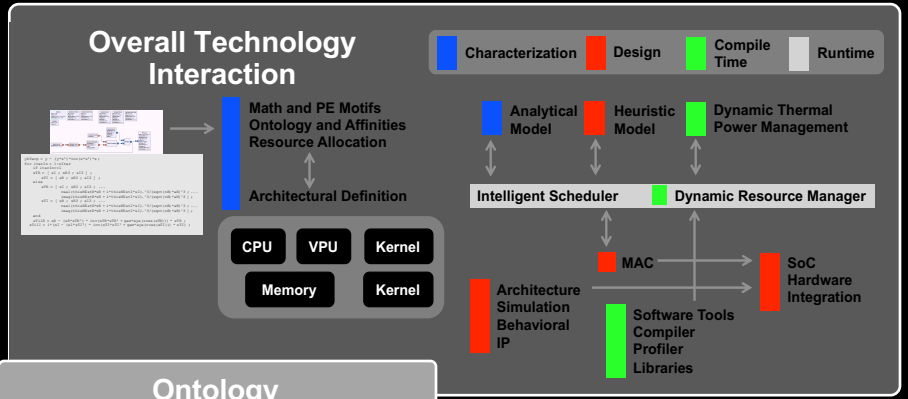
- **Enable new low-cost high-performance systems**
- **Broaden system designers' views of what is possible**

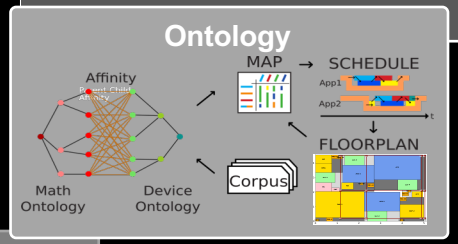
R. Uhrie, D. W. Bliss, C. Chakrabarti, U. Y. Ogras, J. Brunhaver, "Machine understanding of domain computation for Domain-Specific System-on-Chips (DSSoC)," Proc. SPIE Open Architecture/Open Business Model Net-Centric Systems and Defense Transformation 2019

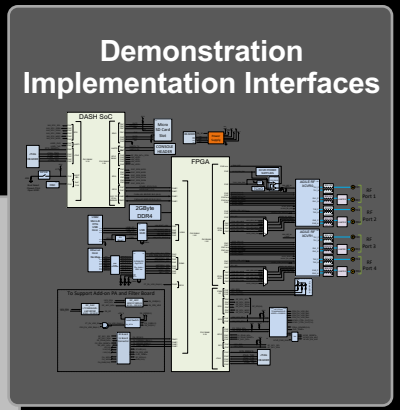
DSSoC DASH Technology

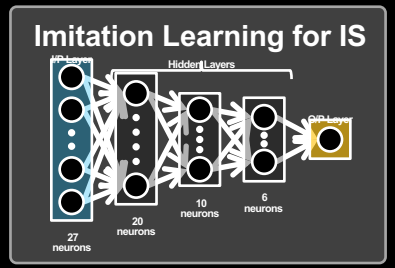
Technological Components

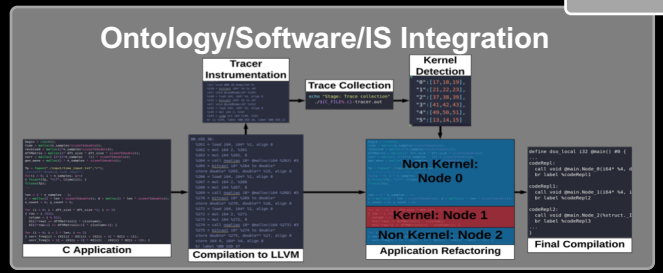
- ***Ontology*** – Develop understanding of application computational structure
- ***Software*** – Produce suite of tools to enable easy application development and debugging
- ***MAC*** – Provide advance on-chip network
- ***Intelligent Scheduler*** – Enable real-time advanced SoC resource management
- ***Hardware*** – Develop advance advanced SoC computational units for suite of RF applications
- ***Demonstration*** – Develop example sophisticated MIMO SDR

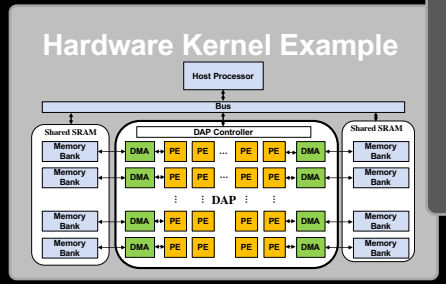










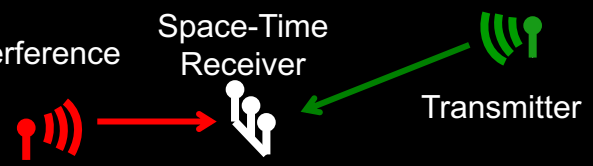


Topics

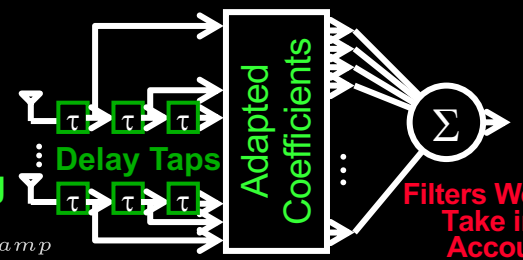
- Introduction
- Underlying Tech Development
- **Important Developing Areas**

Radio Interference-Mitigation Approaches

- **Enable higher RF density by mitigating interference**
- **Exploit space-delay correlations of interference sources to mitigate**
  - Space-time adaptive processing (STAP)



Space-Time Adaptive Processing



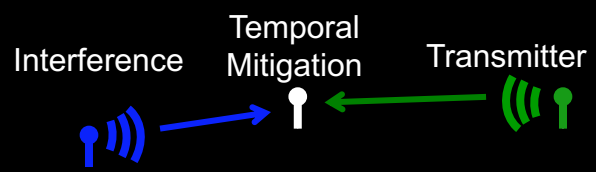
Filters Weights Take into Account Space-Time Correlations

$$\mathbf{Z} \in \mathbb{C}^{(n_{ant} \cdot n_{tap}) \times n_{samp}}$$

$$\mathbf{w} = (\underbrace{\mathbf{Z}\,\mathbf{Z}^H}_{\hat{\mathbf{C}}})^{-1}\,\underbrace{\mathbf{Z}\,\underline{\mathbf{s}}_m^H}_{\underline{\mathbf{v}}_m} \in \mathbb{C}^{(n_{ant} \cdot n_{tap}) \times 1}$$

$$= \hat{\mathbf{C}}^{-1}\,\hat{\mathbf{v}}_m$$

- **Exploit known temporal structure to mitigate**
  - Temporal mitigation (estimation-subtraction)
  - Decodable interference



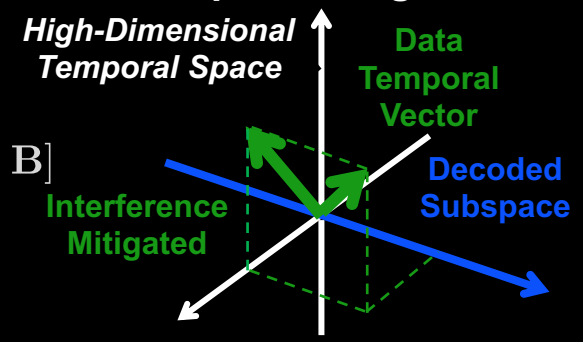
Projects onto Space Orthogonal to Known Interference Sequence

$$\tilde{\underline{\mathbf{z}}} = \underline{\mathbf{z}}\,[\mathbf{I} - \mathbf{B}^H\,(\mathbf{B}\,\mathbf{B}^H)^{-1}\,\mathbf{B}]$$

$$= \underline{\mathbf{z}} - \hat{\underline{\mathbf{h}}} * \underline{\mathbf{b}}$$

$$\mathbf{B} = \begin{pmatrix} \underline{\mathbf{b}}_{\tau_1} \\ \underline{\mathbf{b}}_{\tau_2} \\ \vdots \end{pmatrix}$$

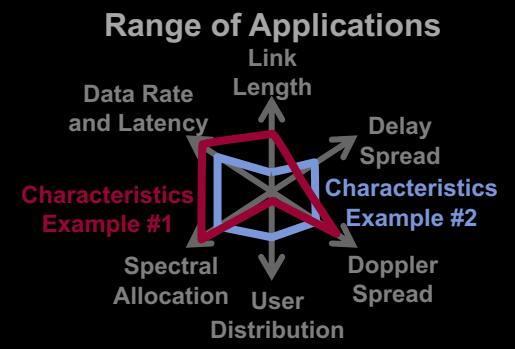
Temporal Mitigation

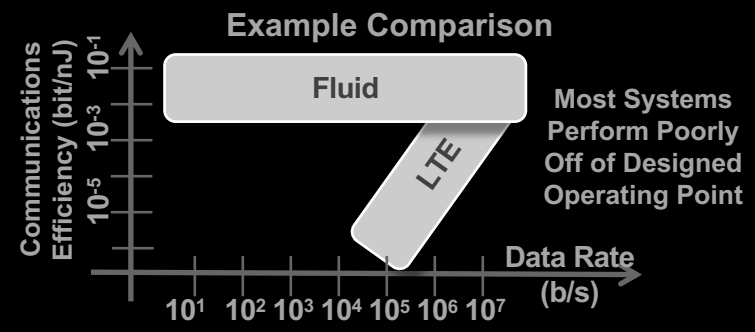


D. W. Bliss and S. Govindasamy, "Adaptive Wireless Communications: MIMO Channels and Networks," Cambridge University Press, Cambridge, 2013.

Fluid Communications Systems

- Address needs of non-human users (IoT)
- Match waveform to environmental needs
- Break rigid standard paradigm
- Employ fluid radio system
  - Need flexibility not higher performance
  - Modify waveform, transceiver, computations to address needs
- Scale consumption to needs
  - Joint hardware/software adaptivity
  - High power efficiency
- Redesign entire radio system
  - Frequency synthesizers are problematic

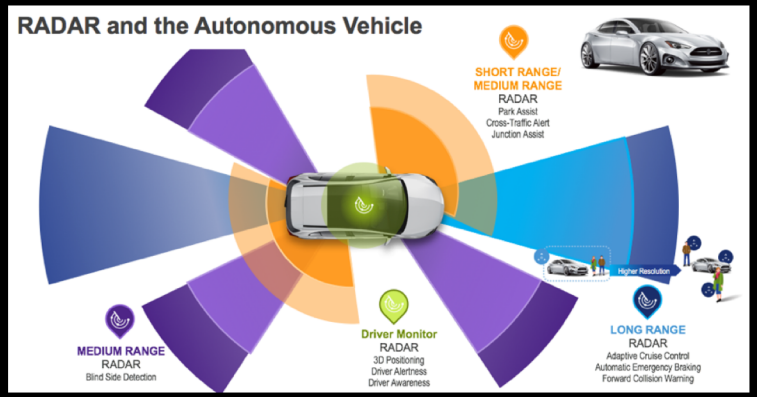




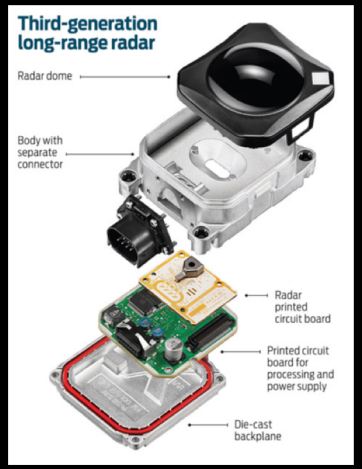
Ganapati Bhat, Sharanya Srinivas, Vamsi Chagari, Jaehyun Park, Thomas McGiffen, Hyunseok Lee, Daniel W. Bliss, Chaitali Chakrabarti, and Umit Y. Ogras, "Fluid wireless protocols: energy-efficient design and implementation," IEEE/ACM Symposium on Embedded Systems for Real-Time Multimedia, 2017.

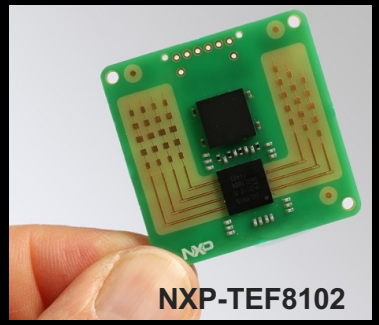
Automotive Radars

- Provide vehicle situational awareness
- Accepted broadly
  - New safety requirement
  - Mass production
- Drive system lower costs
  - Short and “long” range automotive radars ~ $100
  - 24 GHz and 77 GHz
- Need improved system integration and functionality



https://semiengineering.com/here-comes-high-res-car-radar/

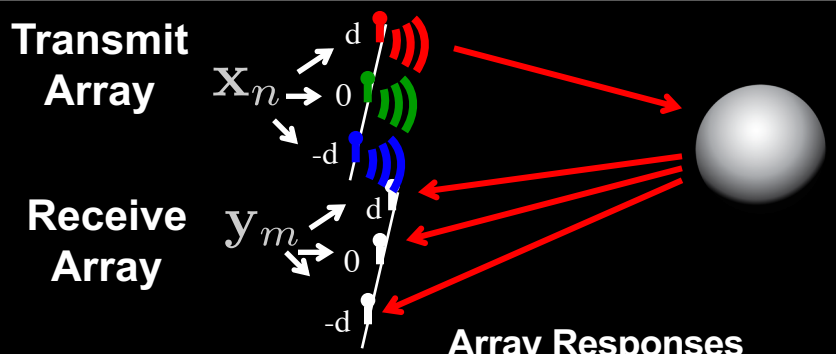




https://spectrum.ieee.org/transportation/advanced-cars/longdistance-car-radar

MIMO Radar Channel

Concept of Virtual Array



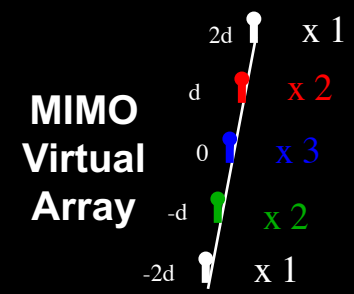
Notional Model

$$\underbrace{\mathbf{z}(t)}_{\text{Received Signals}} = \sum_{\delta} \underbrace{\mathbf{H}(\delta)}_{\text{Channel Matrices}} \underbrace{\mathbf{s}(t-\delta)}_{\text{Transmitted Signals}} + \mathbf{n}(t)$$

$$(\mathbf{H})_{m,n} \propto e^{i\,\mathbf{k}\cdot(\mathbf{y}_m + \mathbf{x}_n)}$$

Array Responses

$$\mathbf{H}(\delta) \propto \begin{pmatrix} e^{i\eta 2d} & e^{i\eta d} & e^{i\eta 0} \\ e^{i\eta d} & e^{i\eta 0} & e^{-i\eta d} \\ e^{i\eta 0} & e^{-i\eta d} & e^{-i\eta 2d} \end{pmatrix} \quad ; \eta = \mathbf{k}\cdot\mathbf{d}$$



- **Use MIMO virtual array to increase degrees of freedom**
  - Convolution of real arrays produces virtual array
- **Disentangle MIMO channel by exploiting transmitter diversity**
- **Consider new geometries**
  - Virtual array may over-represented elements
  - Sparse arrays

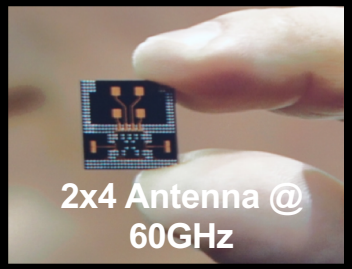
D. W. Bliss and K. W. Forsythe, "Multiple-input multiple-output (MIMO) radar and imaging: degrees of freedom and resolution," *IEEE Asilomar Conference on Signals, Systems & Computers*, 2003

Personal Radars

- **Expect single-chip radars to be the next camera phone tech**
  - RF convergence for mmWave
- **Address new application areas**
  - Human interface
  - Health monitoring
  - Situational awareness

Google ATAP's Soli

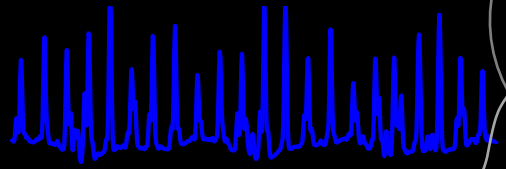
Google I/O

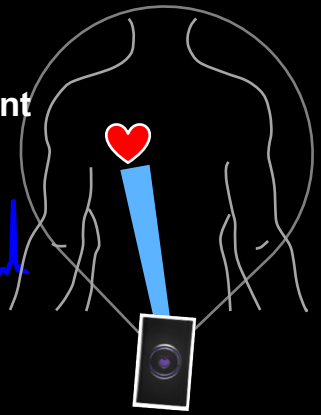


Cardiac Radar

Radar Cardiac Measurement

MIMO Radar

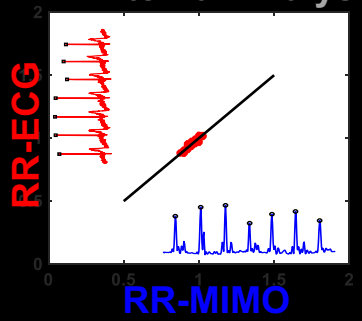




Walabot Imaging Sensor

BLISS Lab

RR Interval Analysis

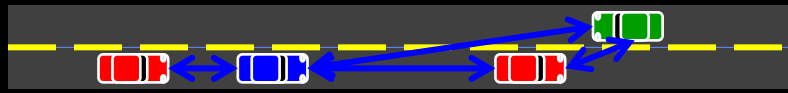


Y. Rong and D. W. Bliss, "Direct RF Signal Processing For Heart-Rate Monitoring Using UWB Impulse Radar," IEEE Asilomar Conference on Signals, Systems, and Computers, Oct., 2018.

RF Convergence

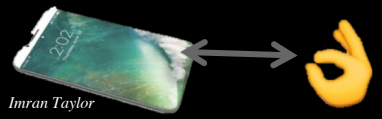
- Provide more effective use of RF spectrum
- Reuse RF signals and receivers
  - Node performs multiple tasks simultaneously with same RF energy
- Remove artificial separation between communications, radar, EW, & RF SA
- Improve rather than degrade performance by friendly RF systems
  - Radios can estimate channels
  - Radars can decode and transmit communications signals
  - Radar waveform is the communications signal

Automotive Comms & Positioning

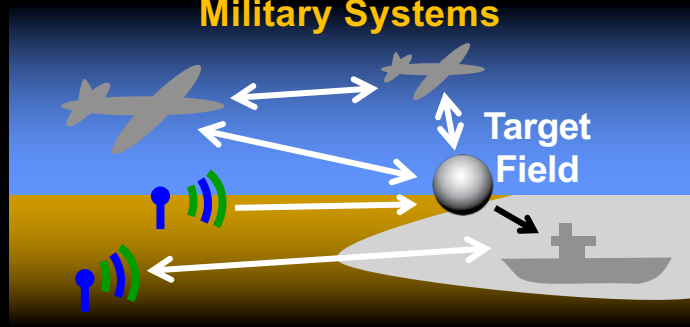


Joint Communications and Radar Systems

Future Phones Recognize Gestures With Radar



Military Systems

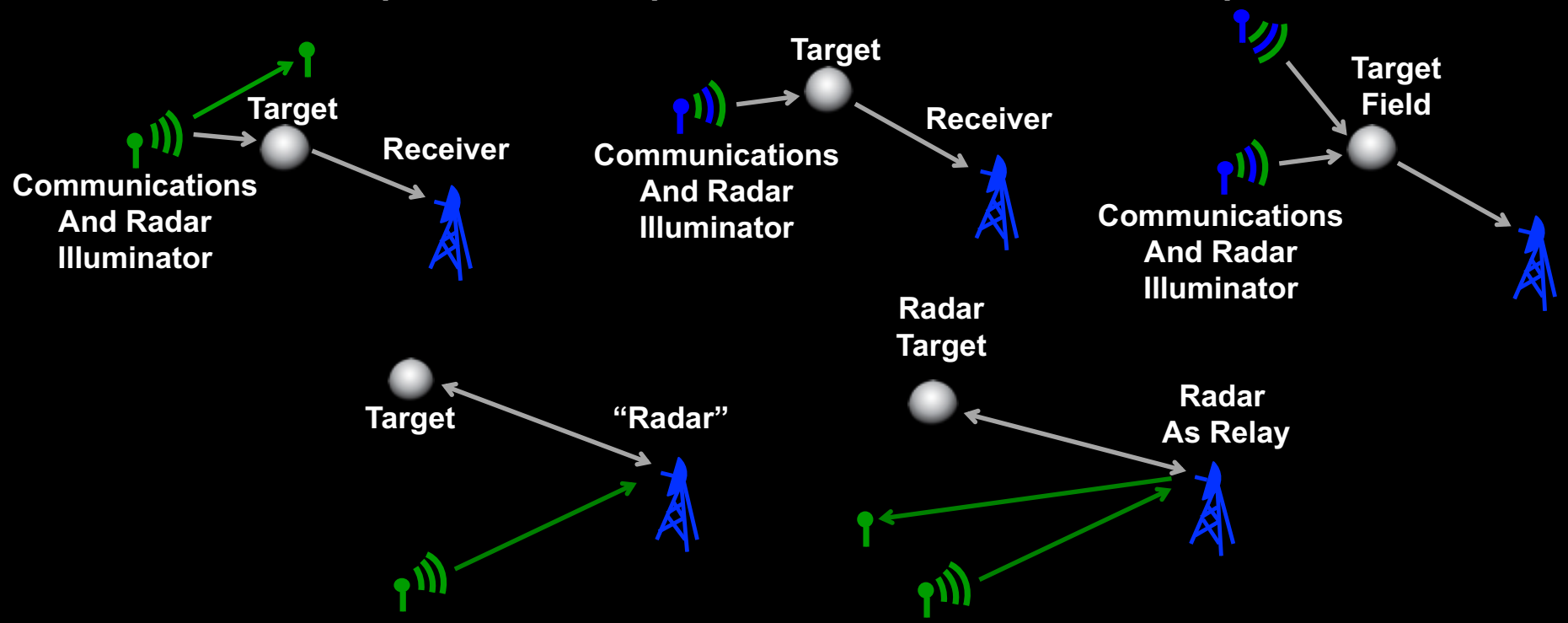


B. Paul, A. R. Chiriyath and D. W. Bliss, "Survey of RF Communications and Sensing Convergence Research," in *IEEE Access*, vol. 5, pp. 252-270, 2017.

Simple Topological Models

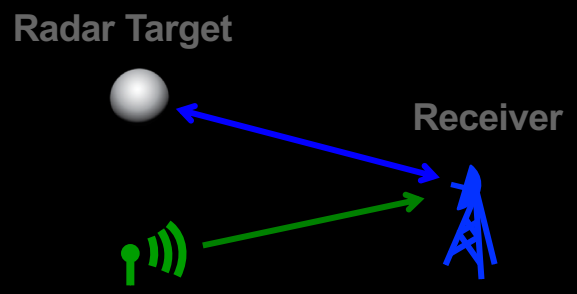
Communications and Radar Examples

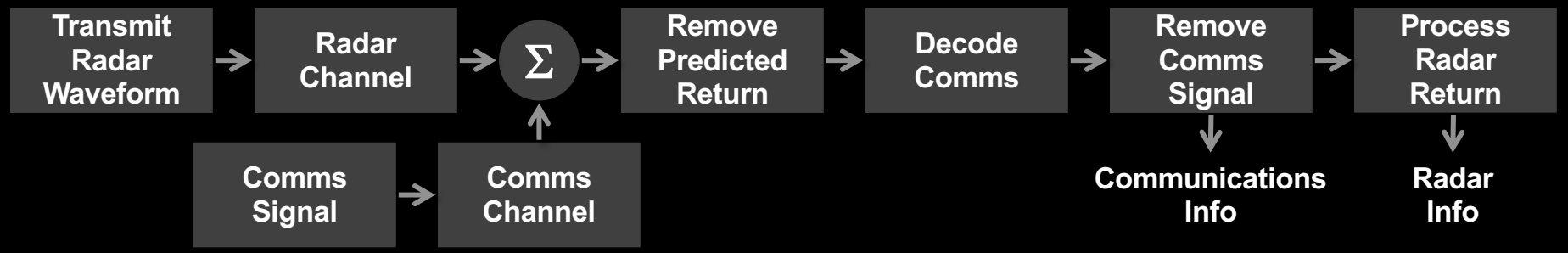
Decompose more complicated networks into basic components



Multi-Access Communications & Radar
Example Approach

- **Recover radar return and communications simultaneously**
- **Explore joint estimation, detection and information theory**
  - **Interactions between sensing and communications**



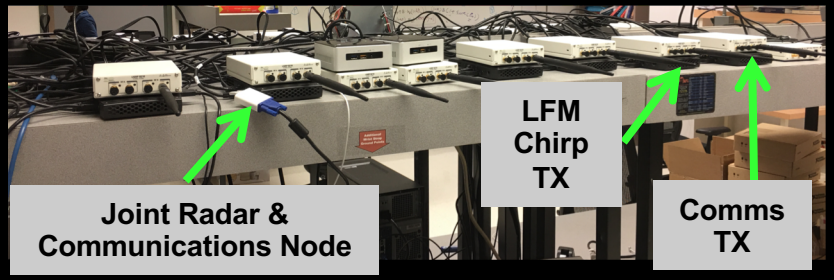


D. W. Bliss, "Cooperative radar and communications signaling: The estimation and information theory odd couple," IEEE Radar Conference, Cincinnati, 2014.

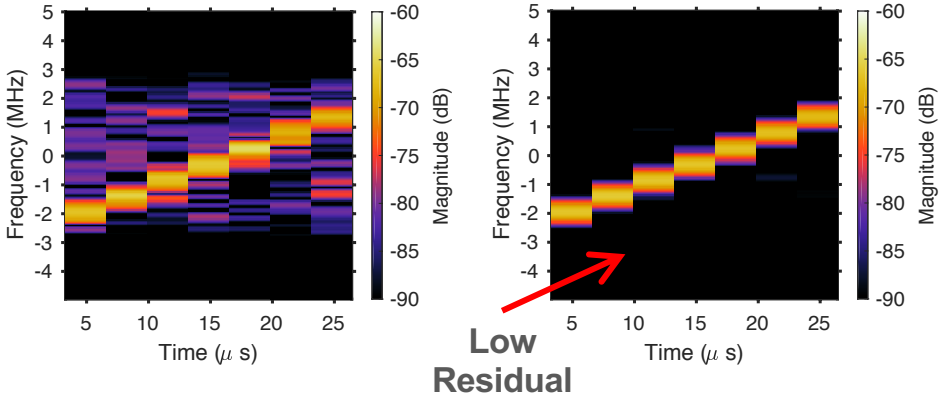
Joint Radar-Communications System
MATLAB-in-the-Loop Experiments

- **Demonstrate feasibility of joint radar-communications system**
  - Use dynamic network of software defined radios
  - Chirp and QPSK waveforms
  - Intelligent power and rate control between systems
- **Decode communications**
- **Remove communications**
- **Observe chirp with little communications residual**

Laboratory Setup



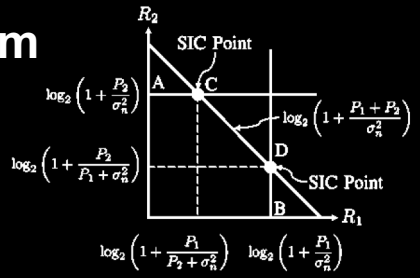
Performance Evaluation

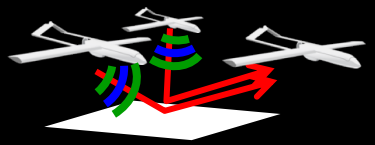


R. M. Gutierrez, H. Yu, A. R. Chiriyath, G. Gubash, A. Herschfelt and D. W. Bliss, "Joint Sensing and Communications Multiple-Access System Design and Experimental Characterization," IEEE Aerospace Conference, Big Sky, 2019.

Multiuser Communications & Multi-Static SAR
MATLAB Simulation

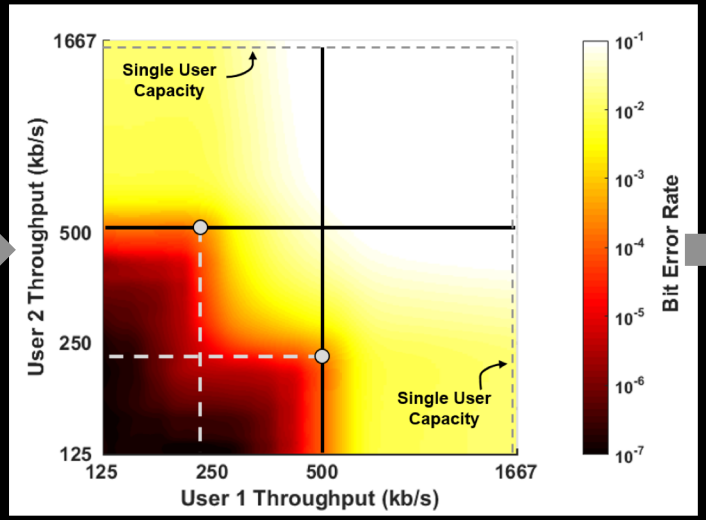
- Design joint radar-communications system
- Develop multi-static channel model
- Approach performance bounds
- Perform SAR imaging



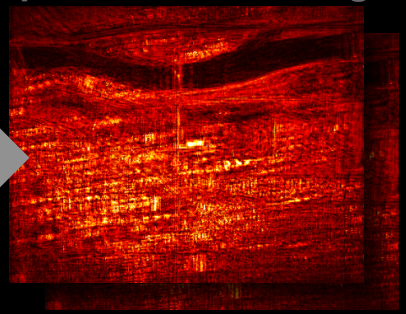


Modeled Scattering Field

Successive Interference Cancellation



Multi-Static Synthetic Aperture Radar Image

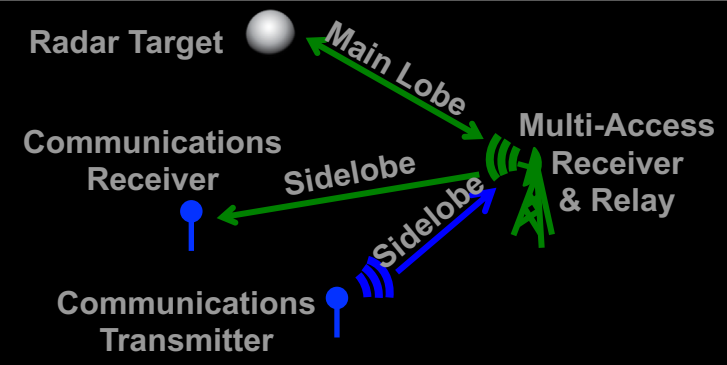


A. Herschfelt and D. W. Bliss, "Joint radar-communications waveform multiple access and synthetic aperture radar receiver," IEEE Asilomar Conference on Signals, Systems, and Computers, Pacific Grove, 2017.

Multi-Access Receive and Relay

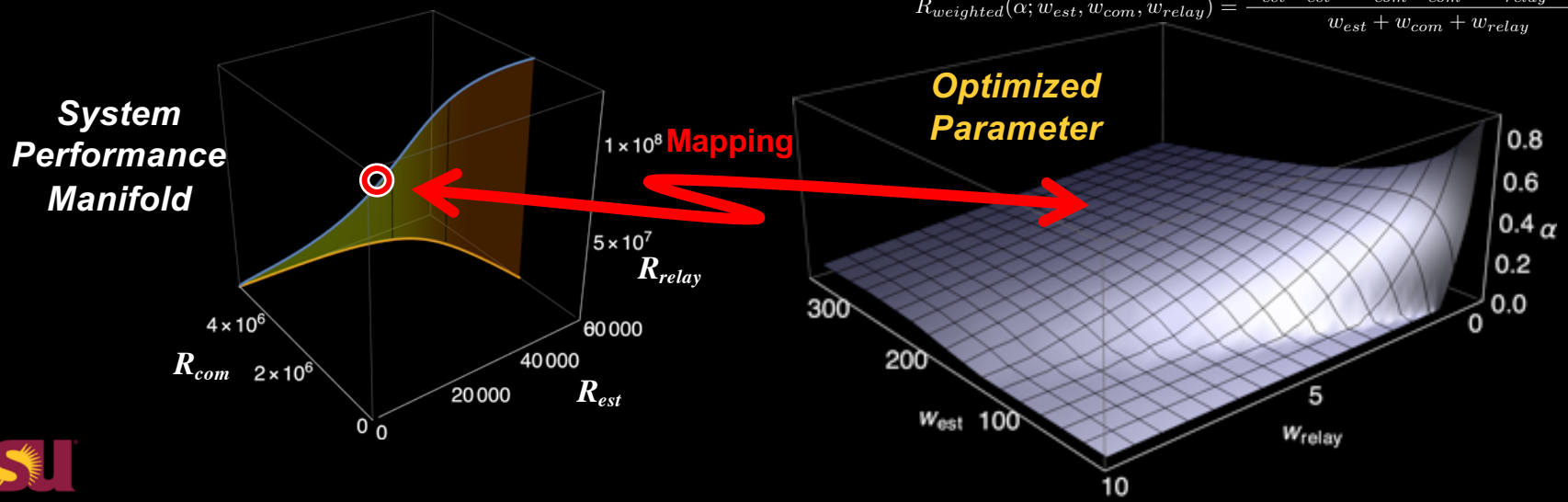
Simple Example

- **Optimize operating point**
  - Maximize objective function
- **Evaluate theoretical joint manifold**
- **Investigate operating point selection**
  - Simple example: multi-access receive and relay
  - Simple objective function



$$\hat{\alpha} = \text{argmax}_{\alpha}\{R_{weighted}(\alpha; w_{est}, w_{com}, w_{relay})\}$$

$$R_{weighted}(\alpha; w_{est}, w_{com}, w_{relay}) = \frac{w_{est}\,R_{est} + w_{com}\,R_{com} + w_{relay}\,R_{relay}}{w_{est} + w_{com} + w_{relay}}$$

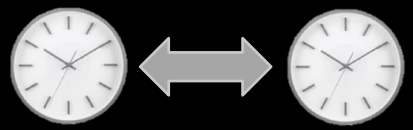


Daniel W. Bliss, "Communication & Radar Co-Design" in Radar and Communications Spectrum Sharing, The Institution of Engineering and Technology (IET), 2018

Distributed Coherent Systems

- **Allow disparate systems to act like they have a common clock**
  - Phase-cohere systems
  - Phase-accurate time transfer

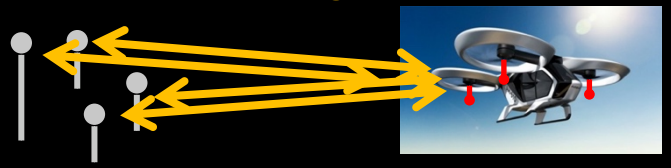
Distributed Coherence



- **Employ co-use communications and positioning waveform**
- **Enable new functionalities**
  - Distributed beamforming: Power ~ N^2
  - Carrier-phase accurate position and navigation

Distributed Beamforming

Joint MIMO Communications and Positioning Waveform

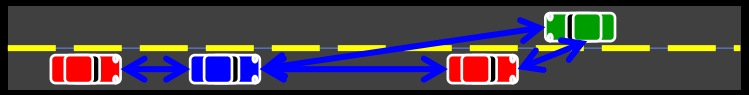


A. Herschfelt and D. W. Bliss, "Joint Positioning-Communications System Design: Leveraging Phase-Accurate Time-of-Flight Estimation and Distributed Coherence," IEEE Asilomar Conference on Signals, Systems, and Computers, Oct., 2018.

Joint Communications and Positioning

- **Exploit flexible radio technology to enable range of time and position critical applications**
  - Automated vehicles
  - Urban air mobility

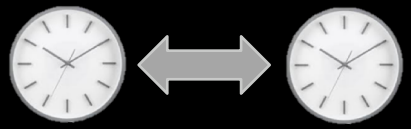
Automotive Comms & Positioning



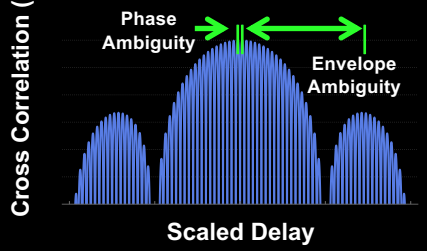
UAS Remote Positioning

- **Pursuing advanced position estimation techniques**
  - MIMO phase recover
  - Distributed coherent
  - Secure & reliable

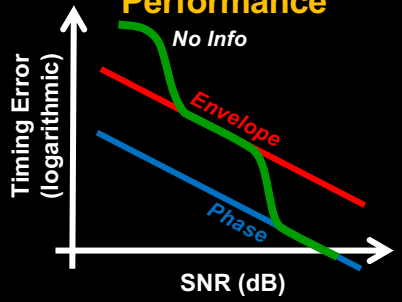
Distributed Coherence



Ambiguity Function



Theoretical Ranging Performance



A. Herschfelt and D. W. Bliss, "Joint Positioning-Communications System Design: Leveraging Phase-Accurate Time-of-Flight Estimation and Distributed Coherence," IEEE Asilomar Conference on Signals, Systems, and Computers, Oct., 2018.

Summary

- Introduced ASU and WISCA
- Observed users are becoming less human
- Identified important driving tech development
- Provided examples of new RF application directions