The Future of RF Systems

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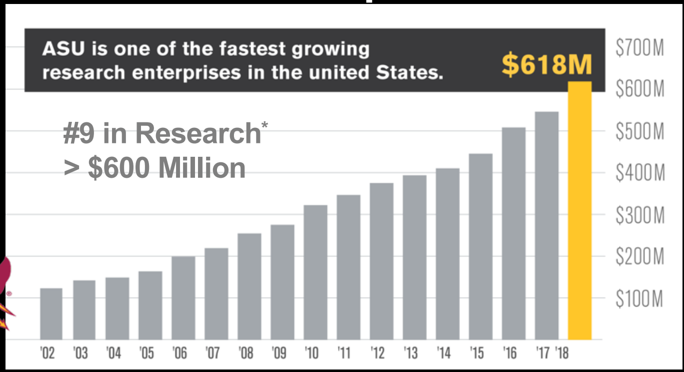
Wireless Information Systems and Computational Architectures

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**
  - $105 M External Research
  - 22,500 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

Year

ASU's WISCA Center

Wireless Information Systems and Computational Architectures

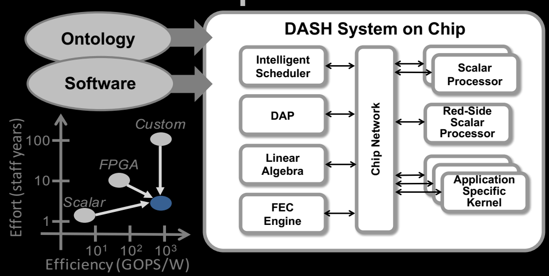
wisca.asu.edu

- **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

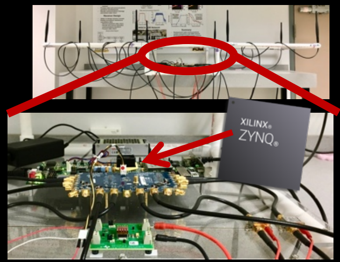
Theory

$$c = \log_2(1 + snr)$$

New Chip Architectures



SDR Flexible Network



Semi-Custom SDRs

Recent and Current Funding Sources

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

Topics

- Introduction
- Underlying Tech Development
- Important Developing Areas

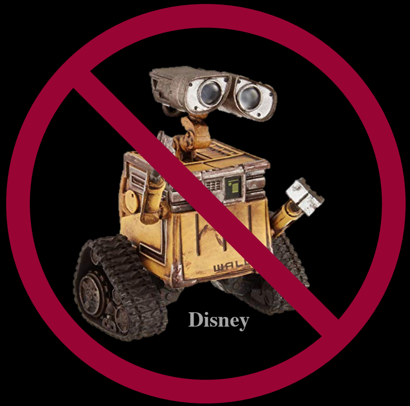
How Will RF Systems Change?

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 SWaP-C**
  - Attritable systems
  - Years on a given charge



Internet Toaster

Why? Really… Why?

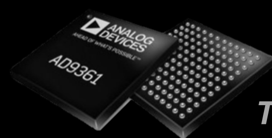
Topics

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

Implications of Commercial Forces

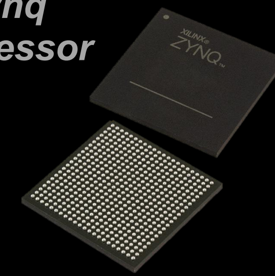
- **Accelerate research with interesting low-cost tools**
  - Broad availability of flexible RF
  - New flexible computational tools

Ettus X310



AD RF Transceiver Technology

Zynq Processor



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

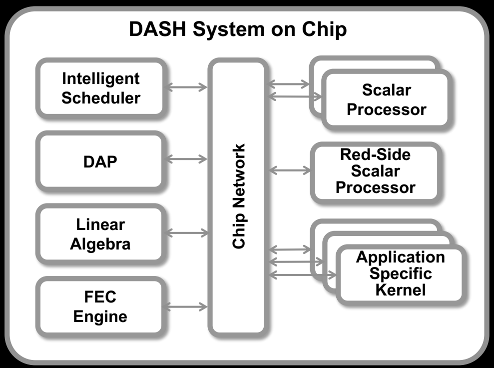
Samsung mmWave 128 Antenna System

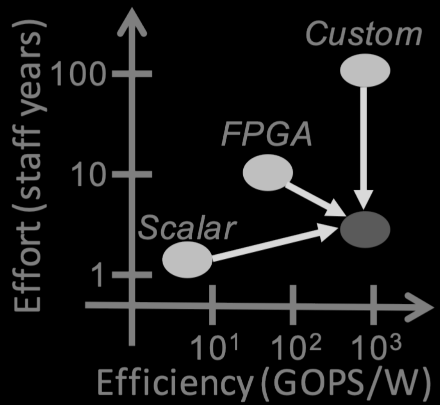
https://www.technologyreview.com/s/515631/samsung-says-new-superfast-5g-works-with-handsets-in-motion/

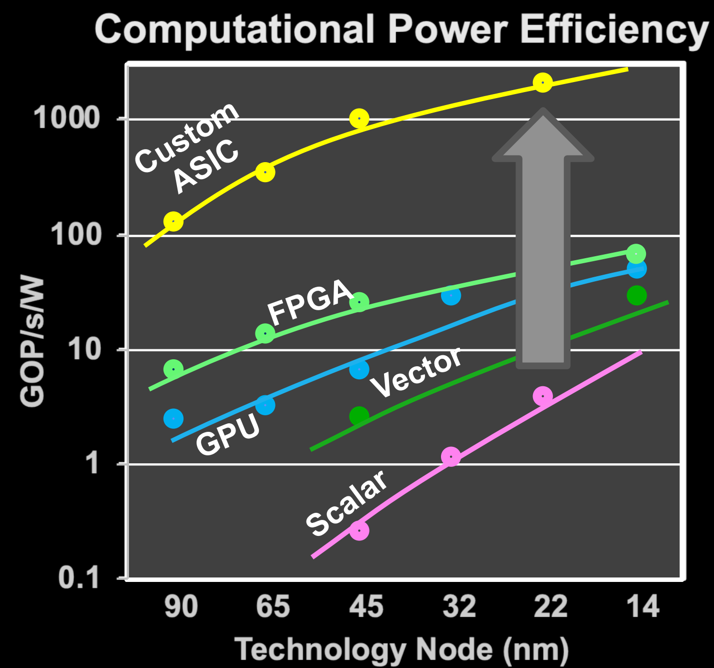
Or, Just Slap a New Sticker on the Phone

Fixing Processor Technology
DARPA DSSoC DASH Program

- Break traditional trade between flexibility and performance
- Lead DARPA processor program
  - Domain-Specific System-on-Chip
  - $17M





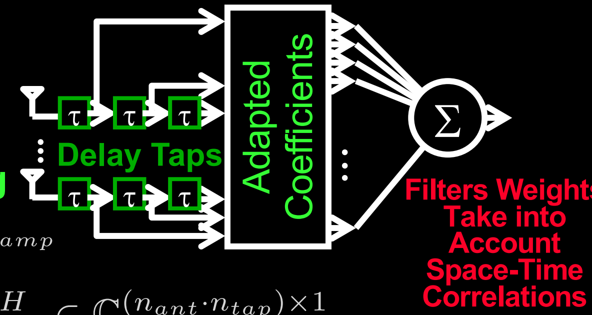


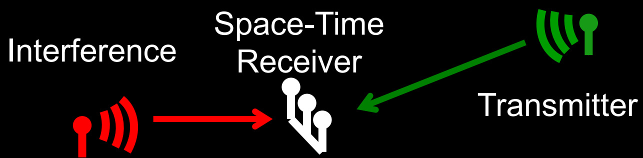
- Enable new low-cost high-performance systems
- Broaden system designers' views of what is possible

RF 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





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

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

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

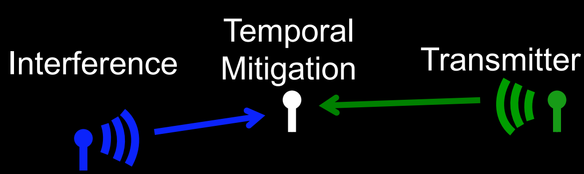
- **Exploit known temporal structure to mitigate**
  - Temporal mitigation (estimation-subtraction)
  - Decodable interference

Projects onto Space Orthogonal to Known Interference Sequence

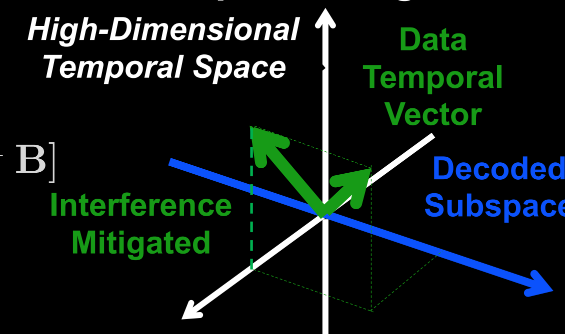
$$\tilde{\underline{\mathbf{z}}} = \underline{\mathbf{z}}\,[\mathbf{I} - \mathbf{B}^H\,(\mathbf{B}\,\mathbf{B}^H)^{-1}\,\mathbf{B}]$$

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

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



Temporal Mitigation



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

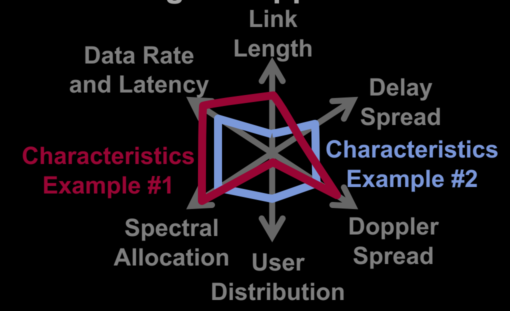
Topics

- Introduction
- Underlying Tech Development
- Important Developing Areas

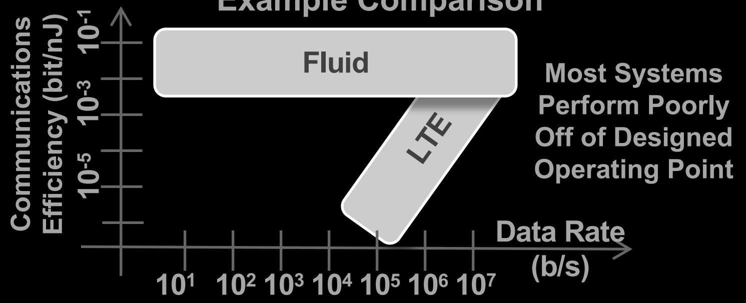
Fluid Communications Systems

- 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

Range of Applications



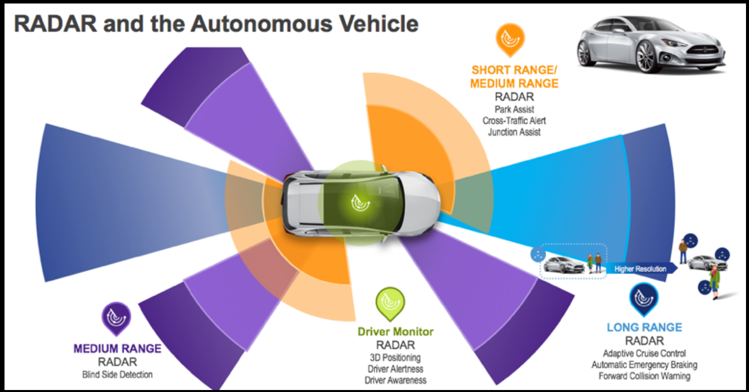
Example Comparison



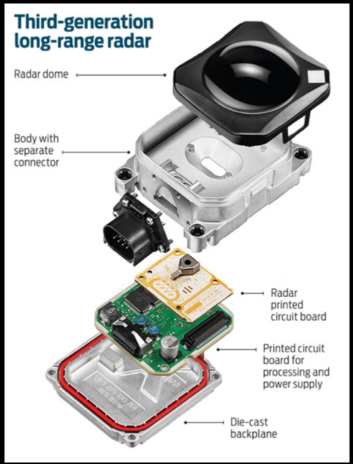
Ganapati Bhat, Sharanya Srinivas, Vamsi Chagari, Jaehyun Park, Thomas McGiffen, Hyunseok Lee, Daniel W. Bliss, Chaitali Chakrabarti, and Umit Y. Ogras, "Fluid wireless protocols: energy-efficient design and implementation," IEEE/ACM Symposium on Embedded Systems for Real-Time Multimedia, 2017.

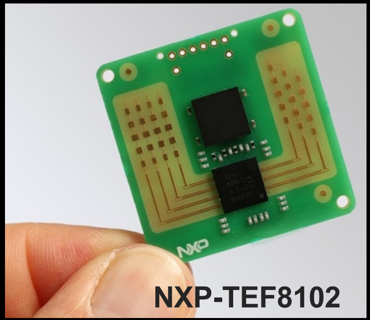
Automotive Radars

- **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

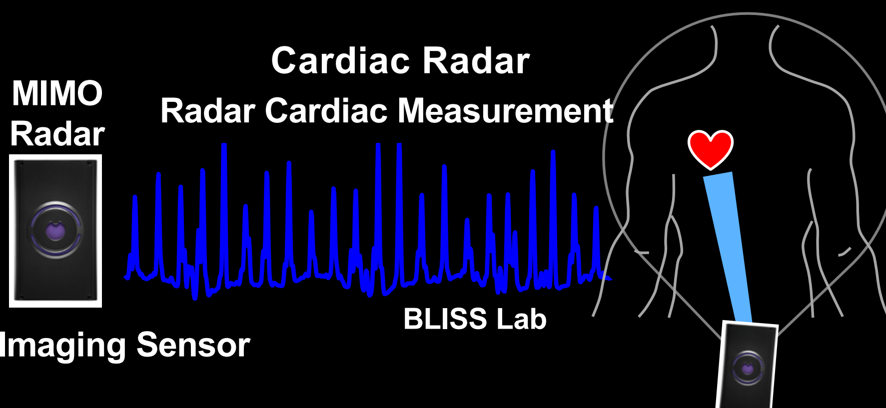
Personal Radars

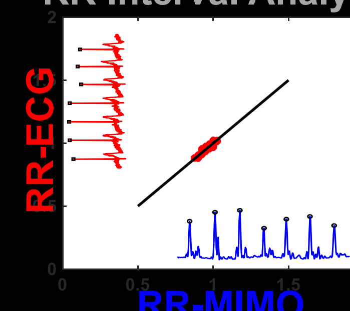
- Expect single-chip radars to be the next camera phone tech
  - RF convergence for mmWave
- Address new application areas
  - Human interface
  - Health monitoring
  - Situational awareness

Google ATAP's Soli

Google I/O

Cardiac Radar

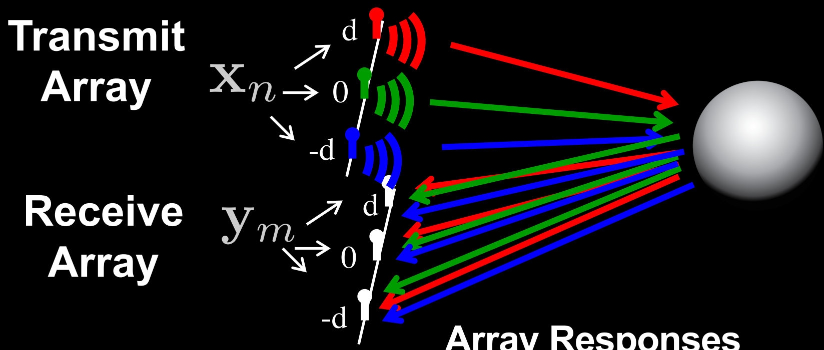




Y. Rong and D. W. Bliss, "Direct RF Signal Processing For Heart-Rate Monitoring Using UWB Impulse Radar," IEEE Asilomar Conference on Signals, Systems, and Computers, Oct., 2018.

MIMO Radar Channel

Multiple-Input Multiple-Output



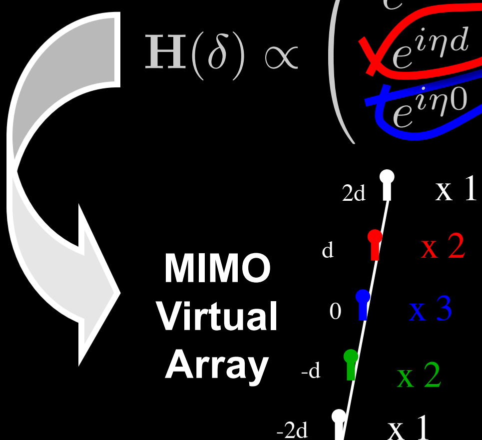
Notional Model

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

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

Array Responses

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



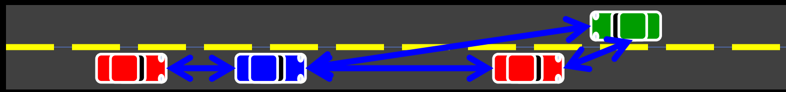
- **Use MIMO virtual array to increase degrees of freedom**
  - Convolution of real arrays produces virtual array
- **Disentangle MIMO channel by exploiting transmitter diversity**
- **Consider new geometries**
  - Virtual array may over-represented elements
  - Sparse arrays

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

RF Convergence

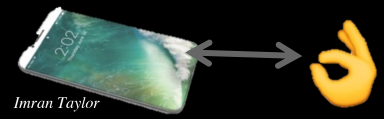
- **Provide more effective use of RF spectrum**
- **Reuse RF signals and receivers**
  - Node performs multiple tasks simultaneously with same RF energy
- **Remove artificial separation between communications, radar, EW, & RF SA**
- **Improve rather than degrade performance by friendly RF systems**
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

Automotive Comms & Positioning

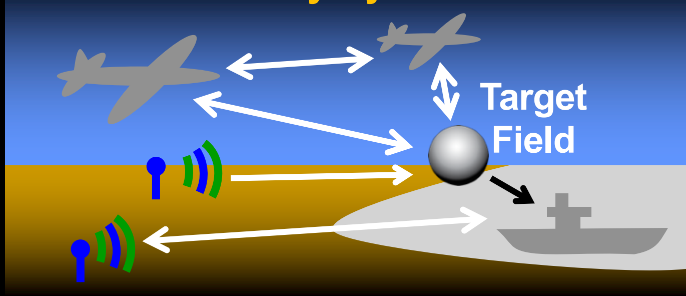


Joint Communications and Radar Systems

Future Phones Recognize Gestures With Radar



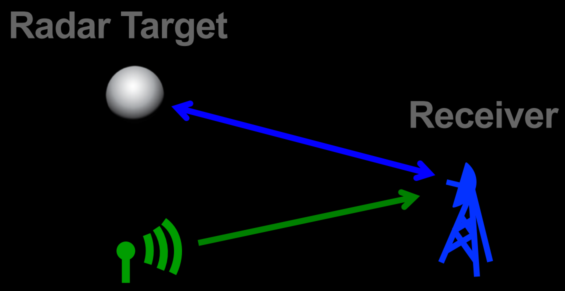
Military Systems

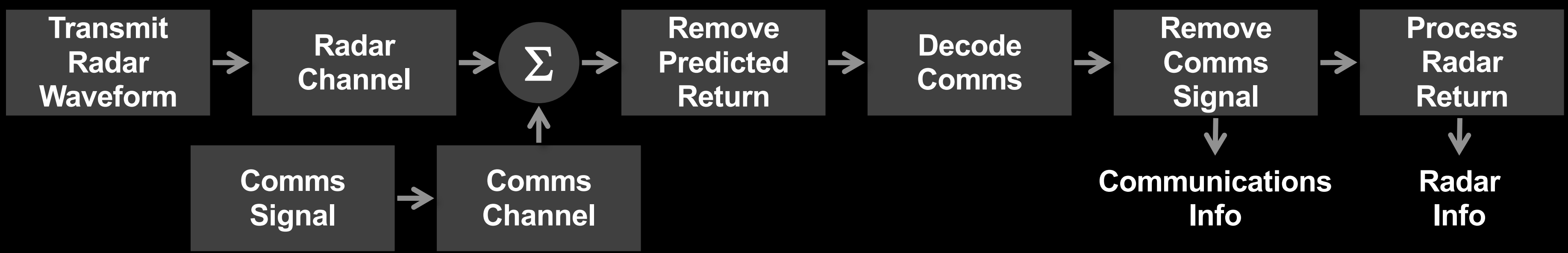


B. Paul, A. R. Chiriyath and D. W. Bliss, "Survey of RF Communications and Sensing Convergence Research," in *IEEE Access*, vol. 5, pp. 252-270, 2017.

Multi-Access Communications & Radar
Example Approach

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



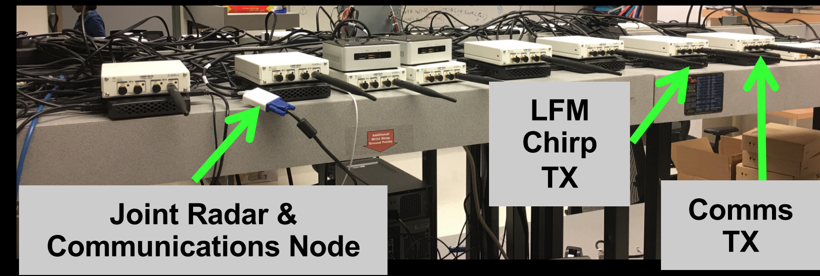


D. W. Bliss, "Cooperative radar and communications signaling: The estimation and information theory odd couple," *IEEE Radar Conference*, 2014

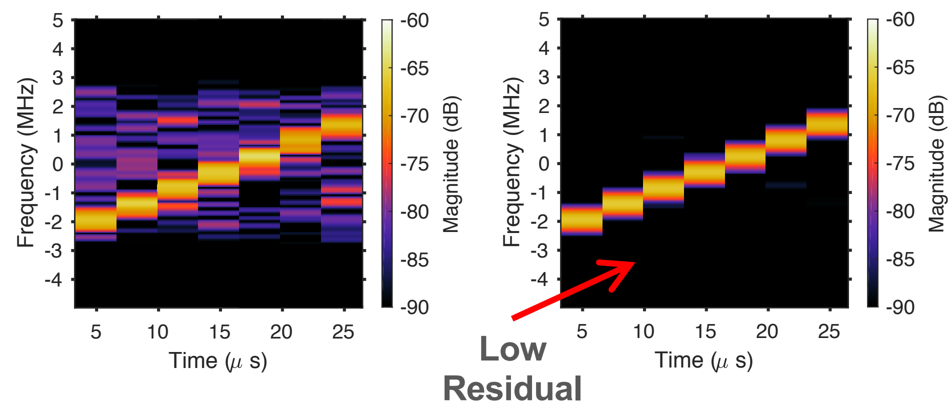
Joint Radar-Communications System
MATLAB-in-the-Loop Experiments

- **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



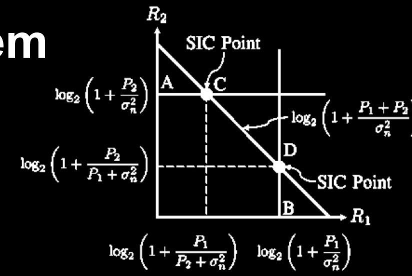
Performance Evaluation

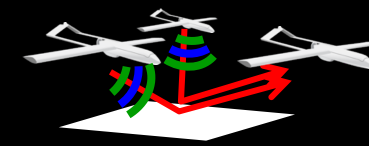


R. M. Gutierrez, A. Herschfelt, H. Yu, H. Lee and D. W. Bliss, "Joint radar-communications system implementation using software defined radios: Feasibility and results," IEEE Asilomar Conference on Signals, Systems, and Computers, 2017

Multiuser Communications & Multi-Static SAR
MATLAB Simulation

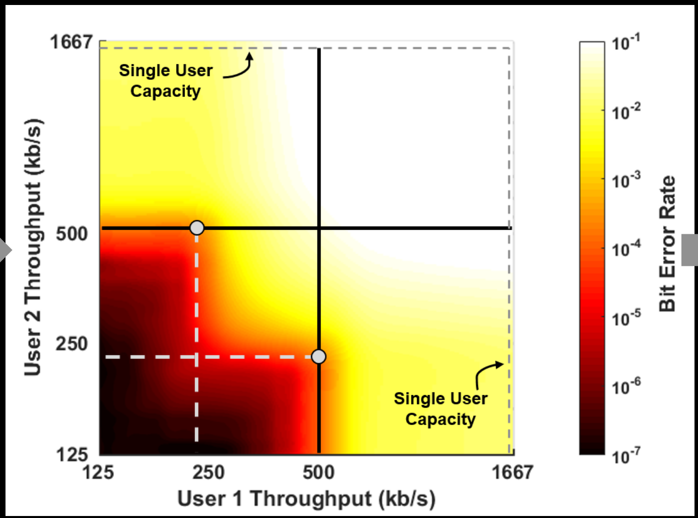
- Design joint radar-communications system
- Develop multi-static channel model
- Approach performance bounds
- Perform SAR imaging



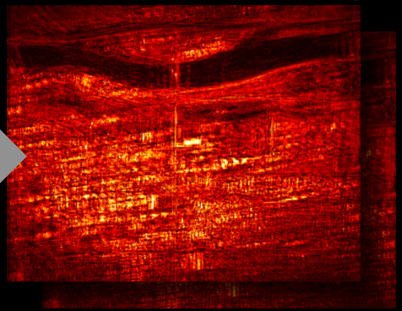


Modeled Scattering Field

Successive Interference Cancellation



Multi-Static Synthetic Aperture Radar Image

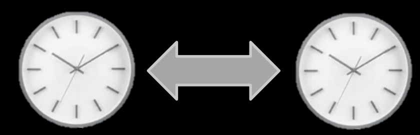


A. Herschfelt and D. W. Bliss, "Joint radar-communications waveform multiple access and synthetic aperture radar receiver," *IEEE Asilomar Conference on Signals, Systems, and Computers*, Pacific 2017

Distributed Coherent Systems

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

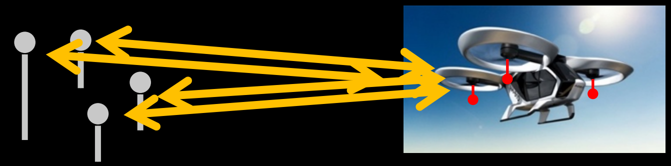
Distributed Coherence



- 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

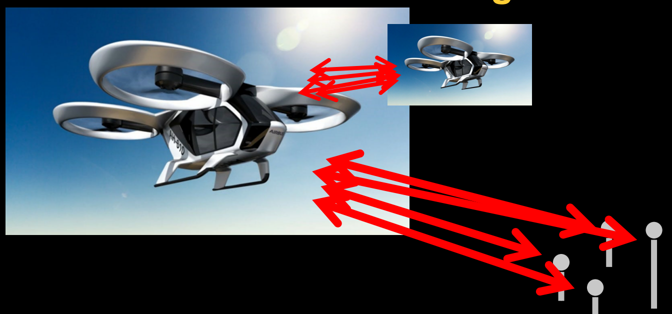


A. Herschfelt and D. W. Bliss, "Joint Positioning-Communications System Design: Leveraging Phase-Accurate Time-of-Flight Estimation and Distributed Coherence," IEEE Asilomar Conference on Signals, Systems, and Computers, Oct., 2018.

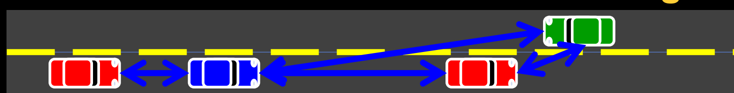
Joint Communications and Positioning

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

UAS Remote Positioning

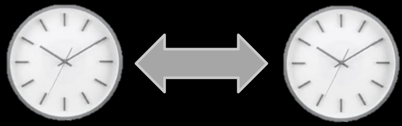


Automotive Comms & Positioning

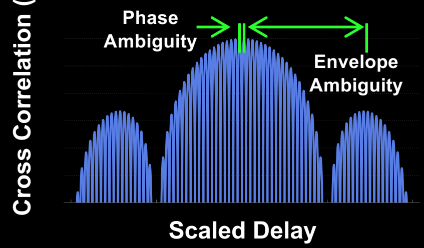


- **Pursuing advanced position estimation techniques**
  - MIMO phase recover
  - Distributed coherent
  - Secure & reliable

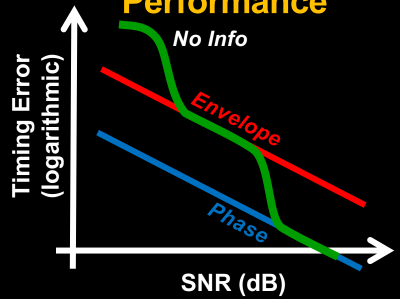
Distributed Coherence



Ambiguity Function



Theoretical Ranging Performance



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Summary

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