# *Future of Spectral Use*

## *Mind the Gap*


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WISCA Center for Wireless Information Systems and Computational Architectures

**President**
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BIG · LITTLE · SENSOR

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# Prof. Daniel W. Bliss

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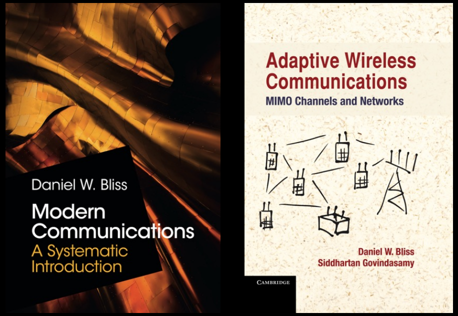
- **Professor in School of Electrical, Computer, and Energy Engineering**
- **Director of WISCA**
- **Published over 250 papers and articles**
- **Provided foundational contributions to**
  - Multiple-input multiple-output radar
  - Adaptive MIMO communications
  - RF convergence (spectrum sharing, ISaC, …)
  - Distributed-coherent systems
  - In-band full-duplex systems
  - Advanced positioning, navigation, and timing
- **Spun out companies**
  - President/CEO of Dash Tech Integrated Circuits, Inc. and Big Little Sensor Co.

**Textbooks**




**IEEE Warren D. White Award for Excellence in Radar Engineering**


**Undergrad**

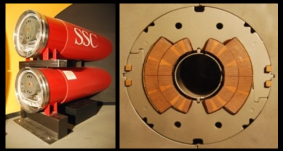
Arizona State University

EE – 1989

**Rocket Avionics**

**Early Work**

**Particle Accelerators**




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

**Grad School**

UC San Diego

MS and PhD Physics, 1995 & 1997

Cornell University Founded A.D. 1865

**Prior Position**

LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

1997-2012

**Currently**

Arizona State University

Electrical Engineering
2013-

**Startups**

DASH Tech IC

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WISCA — Center for Wireless Information Systems and Computational Architectures

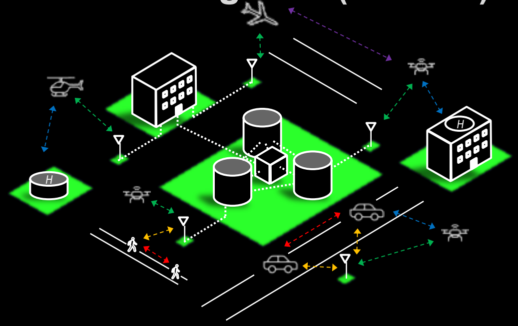
# How Do We Get There?

- Review Goals and Implications of Heilmeier Questions
- Underlying Physics of Applications
- Explore New Enabling Technologies
- Explore Metrics of Performance
- Investigate Examples

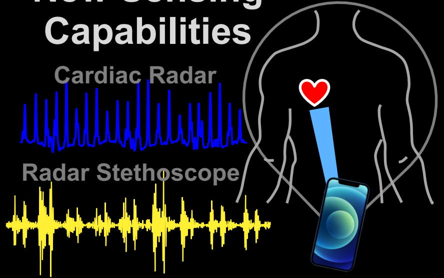
# Future Wireless "Needs"… OK, Desires

- **Want faster, more flexible, more available communications**
- **Want new functionalities that we didn't know we wanted**
  - Communications; sensing; positioning, navigation, and timing (PNT); environmental situational awareness; and ?
- **Want lower cost, size, weight, and power**

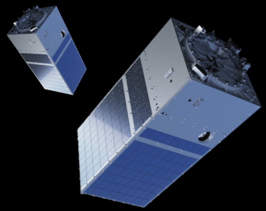
**RF Convergence (or ISaC)**



**New Sensing Capabilities**




**Next Generation Communications**



*Internet Toaster*


**Autonomous Vehicles**

**Augmented Reality**

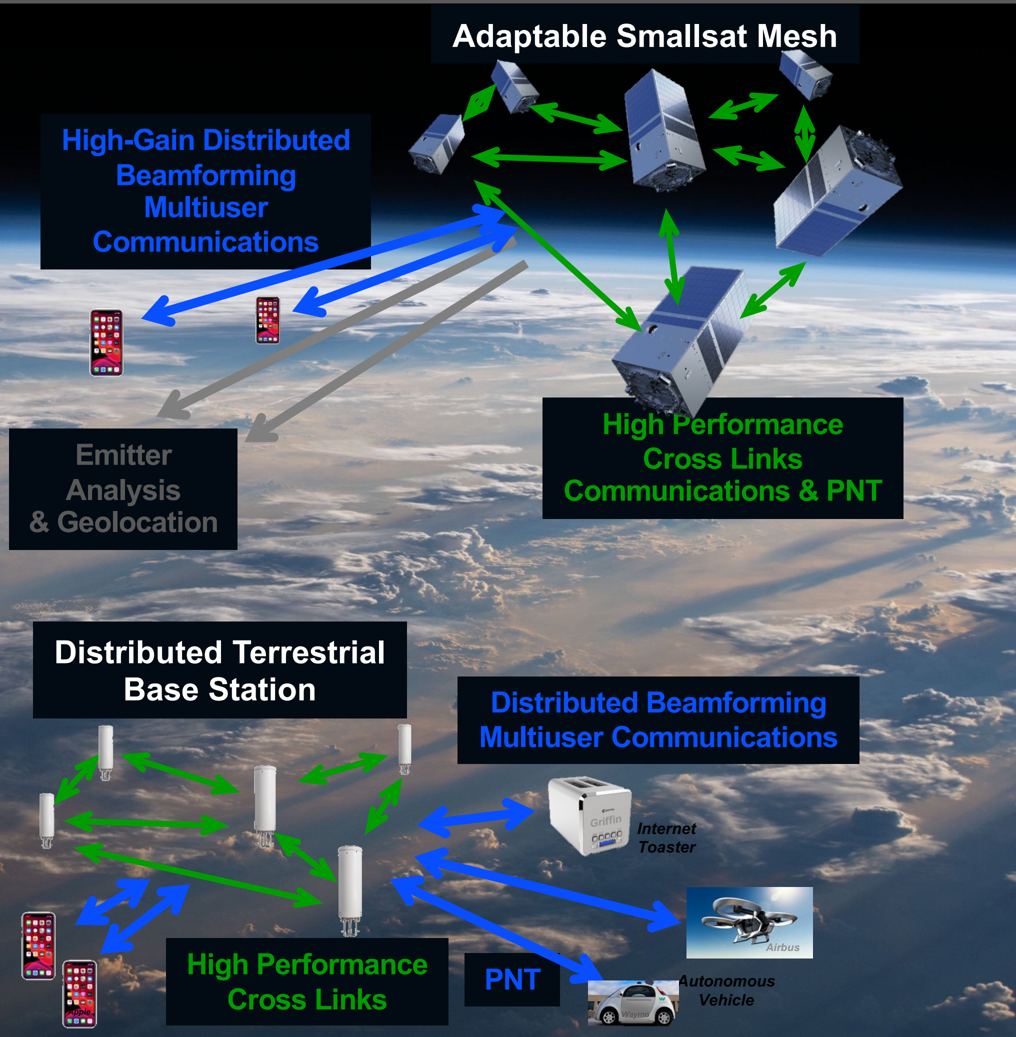
**Fully Immersive 3D Interactive Cat Café Simulations**

**Who knows why, but you know it'll happen**

# Advanced Reconfigurable Systems

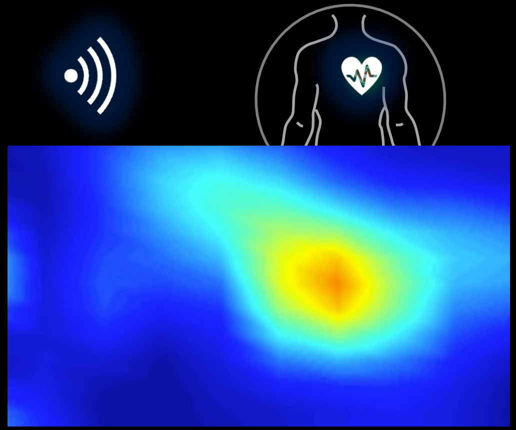
## *DC to Daylight*

- **Reinvent spectral employment by co-design of multi-function system**
  - Provide transparent interface to spectrum
  - Higher data rate, better sensing, improved resilience
- **Enable RF convergence**
  - New functionalities
  - Multi-function systems
  - Communications, radar, PNT, etc…
- **Enable flexible distributed carrier phase-coherent systems**
  - Distributed wireless antenna arrays
- **Integrate proliferated low C-SWaP space**
- **Develop advanced flexible systems**
  - Bandwidth, power-scaling, dynamic range, …
  - Flexible RF and optical
  - Flexible computations

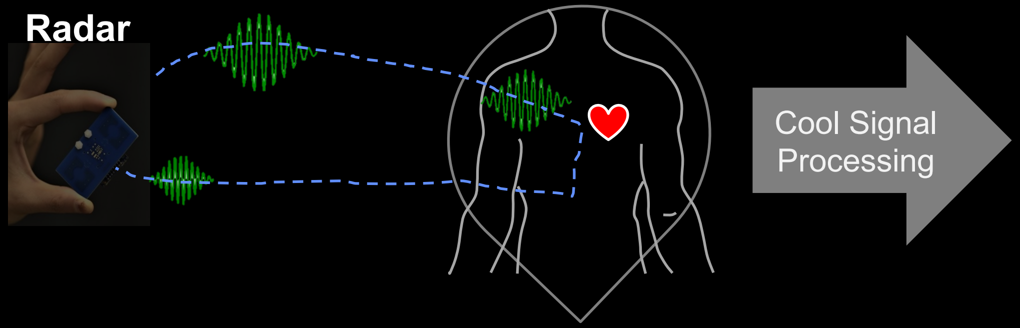


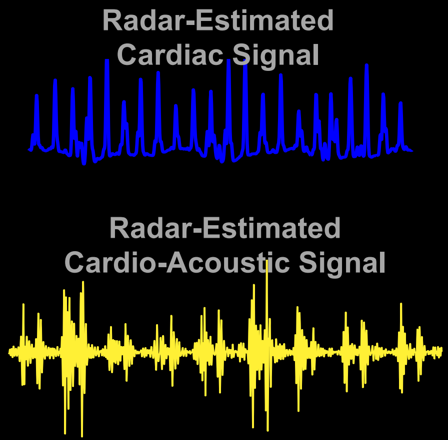
# Physiological Radar

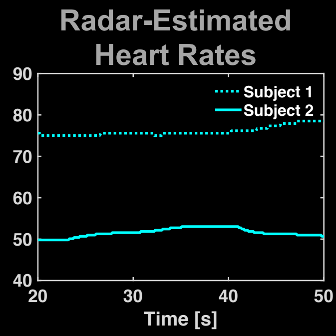
- **Extract hidden environmental information**
  - Extrasensory perception?
- **Use low-cost small-scale radar systems**
  - Could you use your phone as a tricorder?
- **Employs reasonably sophisticated algorithms**

Radar Cardiac Movie




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.

# Heilmeier Questions

- **Defined key questions about technology/project development**
  - What are you trying to do?
  - How is it done today, and what are the limits of current practice?
  - What's new in your approach and why it will be successful?
  - Who cares? What difference will it make?
  - What are the risks and the payoffs?
  - How much will it cost?
  - How long will it take?
  - What are the midterm and final "exams" to check for success?

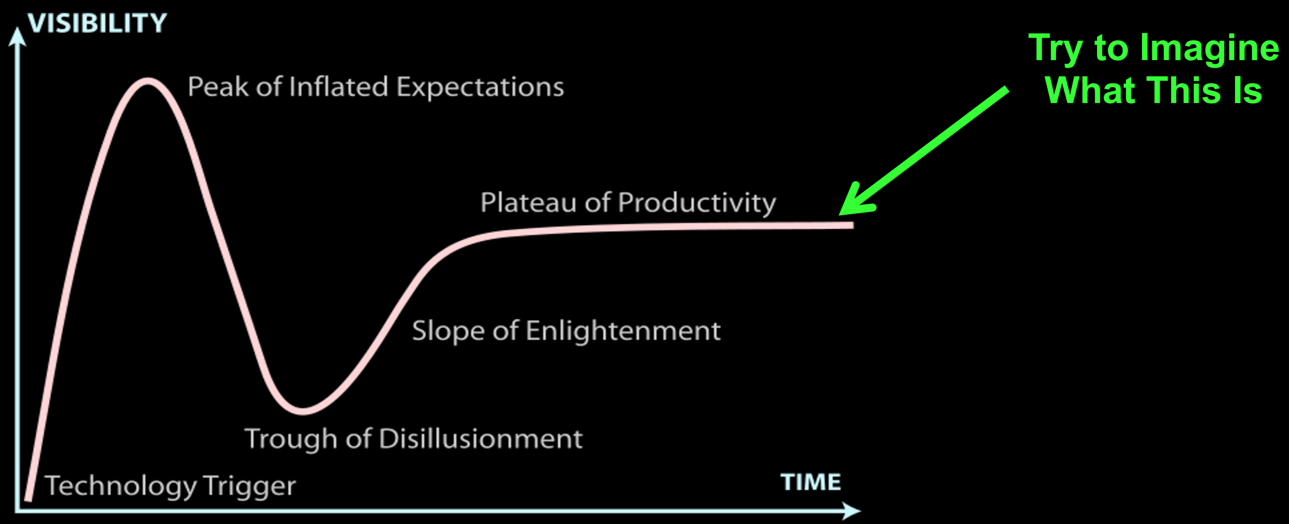
- **Answer these questions when consider your research**

- **Continuously consider to improve your research approach**


**George Heilmeier**
**Director of DARPA, 1975-1977**

# Focus Our Research Questions

- Here, focus on subset of Heilmeier questions
  - How is it done today, and what are the limits of current practice?
  - What's new in your approach and why it will be successful?
  - Who cares? What difference will it make?
- Avoid the sea of “good” ideas that contributed little
- Shoot for end of the Hype Curve




wikipedia

# How is it done today, and what are the limits of current practice?

- **Currently employ range or rigid single-function stove-piped systems**
  - Requires new signal and processing chain for each function
  - Limited ability to upgrade
  - Limited ability to adaptive to changing environments or system needs
  - Uses little outside information

- **Requires remote (cloud) processing for fusion and flexible processing**
  - Huge facility full of 19-inch racks of computers
  - Data movement is expensive and prone to security issues
  - Introduces significant latency to decision making

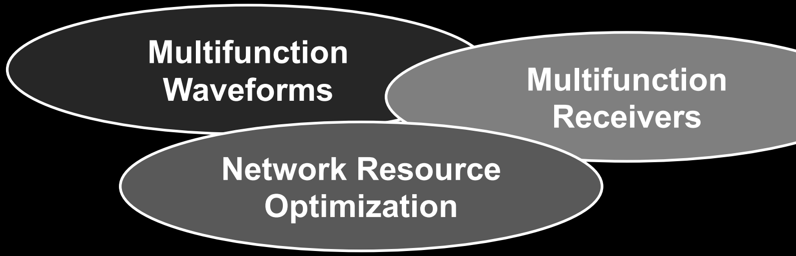
- **Ignores new functionalities enabled by integrated solutions**
  - More processing at edge

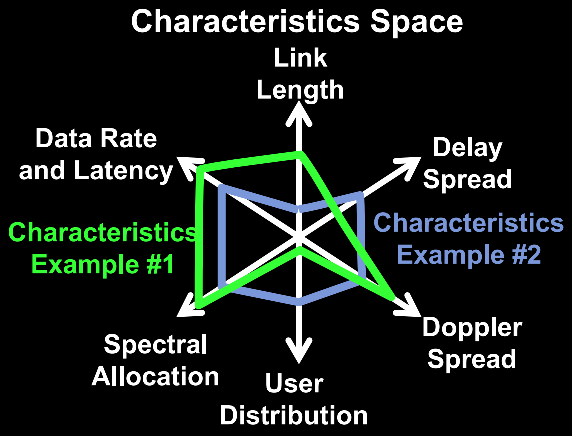
ETA Until Next Phone Upgrade?

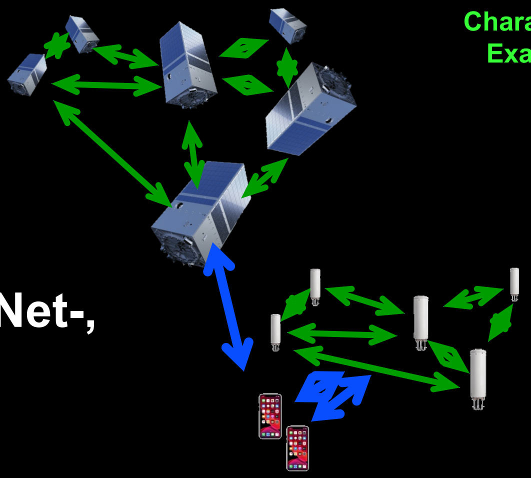
What Clouds Look Like

# What's new in your approach and why it will be successful?

- Mix communications, radar, relative PNT, etc. into single system
- Extend functionality of system by using spectrum in multiple ways
- Fluidly adapt to needs of environment
- Leverage evolving technologies
  - Flexible frontends
  - Efficient, flexible processing
  - Distributed coherence
- Leverage heterogeneous connectivity: MANet-, terrestrial-, and satellite-based

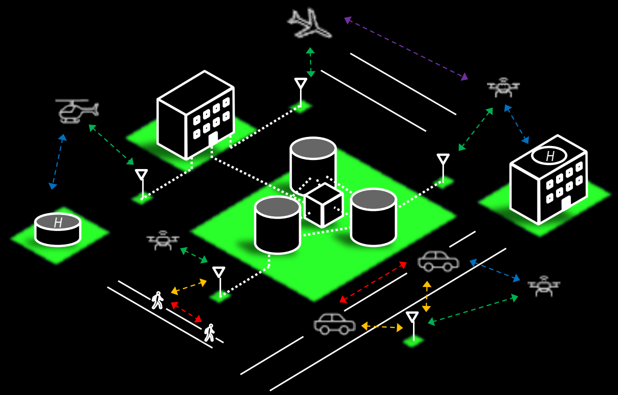


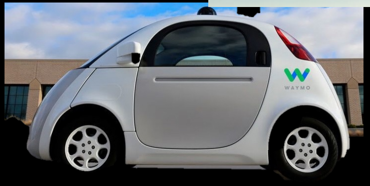



# Who Cares?

- **Applies to a wide range of users**
  - Enabling wide range of end-users', carriers', and spectrum managers needs
- **Reduce system cost - size, weight, and power (C-SWaP)**
  - Fluidly adjust functionality to system needs
- **Integration of functionality into single device**
  - Commercial "phones"
  - Smart homes and home security
  - Smart cities
  - Autonomous and semi-autonomous automotive applications
  - Uncrewed aircraft systems (UASs)
  - Flying cars (VTOL, EVTOL)



# How Do We Get There?

- Review Goals and Implications of Heilmeier Questions
- **Underlying Physics of Applications**
- Explore New Enabling Technologies
- Explore Metrics of Performance
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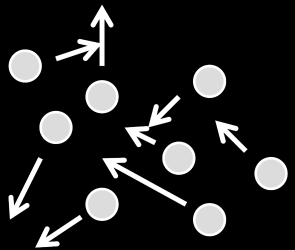
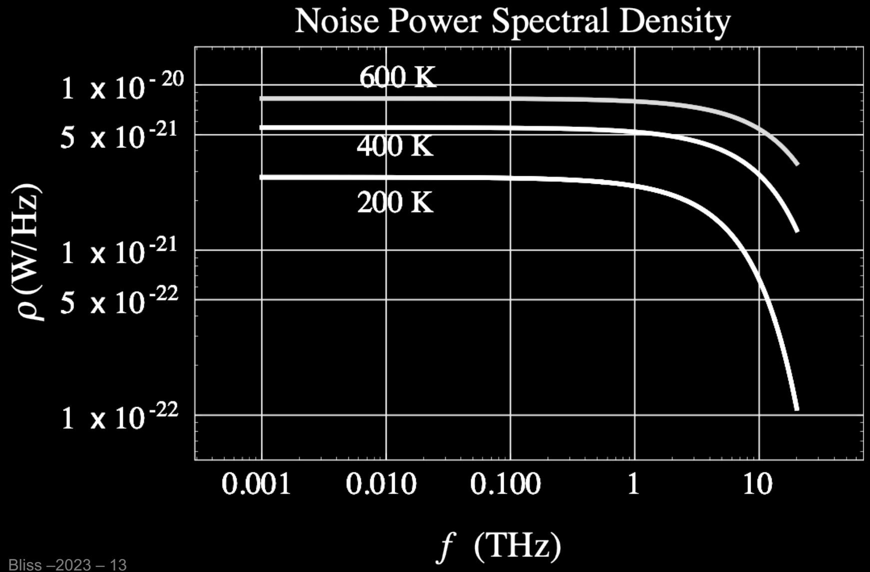
# Noise

- **Identify fundamental challenge to communications, detection, and estimation performance**
  - Thermal noise, not interference

**Large Number of Charged Particles**






## Fundamental Distribution of Noise

Noise-Power Density; Planck Const.; Absolute Temperature; Boltzmann Const.

$$\rho_{\text{noise}}(f) = \frac{h\,f}{e^{\frac{h\,f}{k_B\,T}}-1}$$

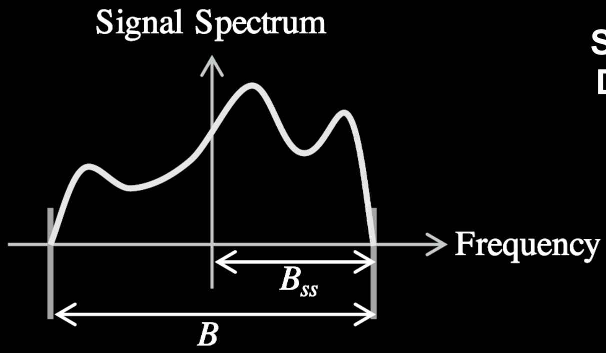
$$\approx \frac{h\,f}{1+\frac{h\,f}{k_B\,T}-1} = k_B\,T\,; \quad \frac{h\,f}{k_B\,T} \ll 1$$

**Typical Noise Power Approximation**

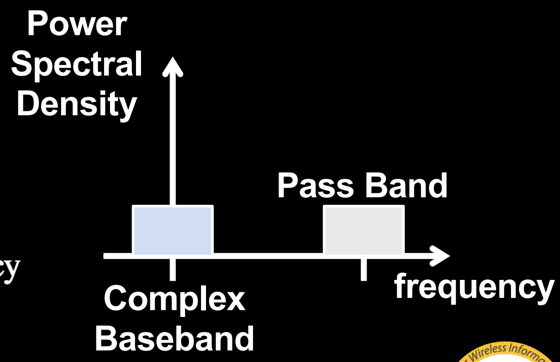
$$P_{\text{noise}} = k_B\,T\,B$$

Double-Sided Bandwidth

**Nyquist Rate**



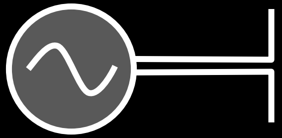

$$R_{Nyq} = 2\,B_{ss} = B$$



# Antennas

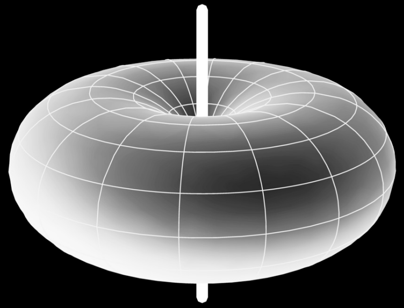
- Convert voltages to magical waves wafting through the air

- Consider the dipole antenna



**Small-Dipole Approximation Radiation Pattern**

$$P_{\text{rad}}(\phi, \theta) = \cos^2(\theta)$$



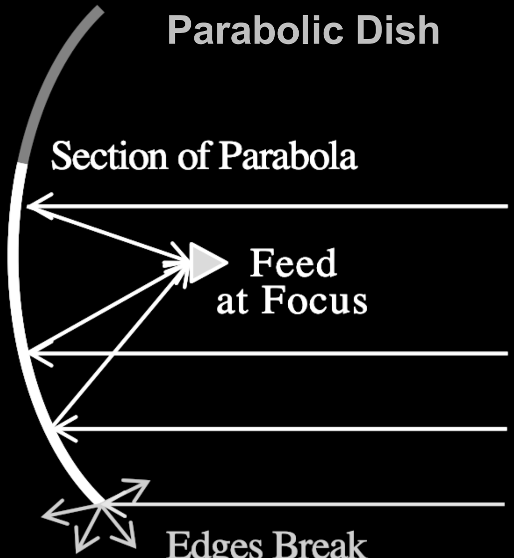
- Relate gain to effective area
  - Makes more sense for large antennas

Effective Area

Gain $$G = 4\pi \frac{A_{\text{eff}}}{\lambda^2}$$

Wavelength

**Parabolic Dish**



# Friis' and Phenomenological Equations

- **Evaluate attenuation**
  - Power is reduced

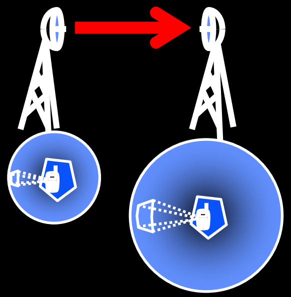
Received Signal

$$z(t) = \overbrace{a}^{\text{Attenuation}}\,\underbrace{s(t)}_{\text{Transmitted Signal}} + \overbrace{n(t)}^{\text{Noise}}$$

- Line-of-sight channel attenuation
  - Friis' Equation

Attenuation In Power

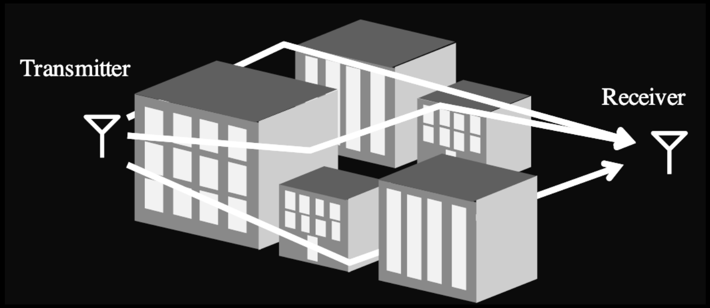
$$\|a\|^2 = \frac{\overbrace{G_t\,G_r}^{\text{Transmit and Receive Gains}}}{(4\pi\,\underbrace{r}_{\text{Distance}}/\underbrace{\lambda}_{\text{Wavelength}})^2}$$



- Complicated scattering
  - Approximate model

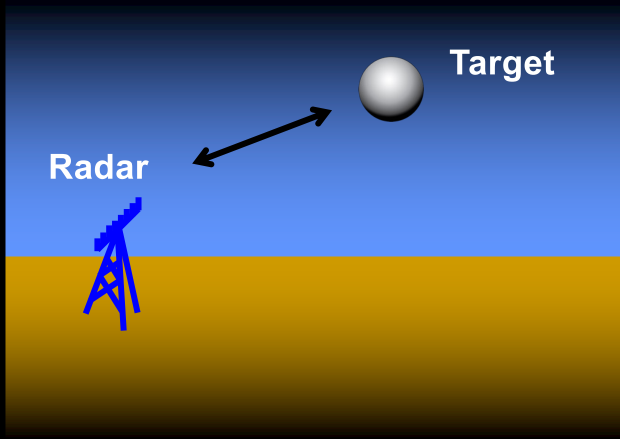
Attenuation In Power

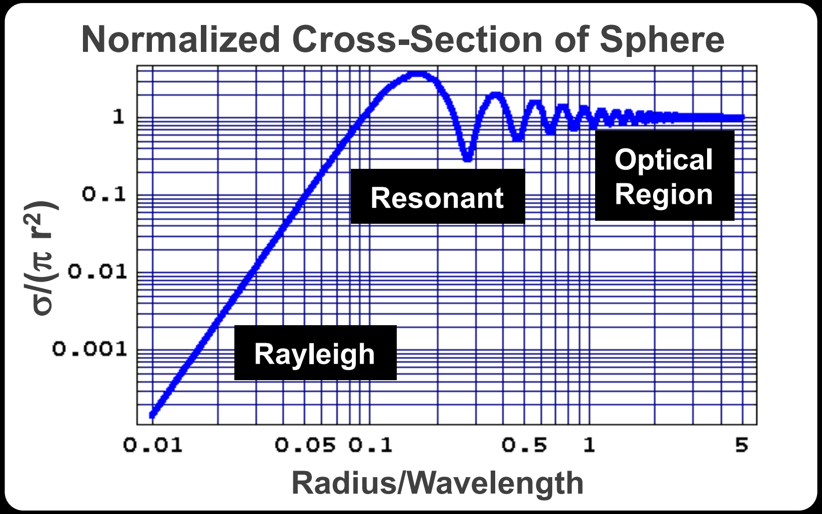
$$\|a\|^2 = k\,\frac{1}{(\underbrace{r}_{\text{Distance}}/\underbrace{\lambda}_{\text{Wavelength}})^\alpha}$$

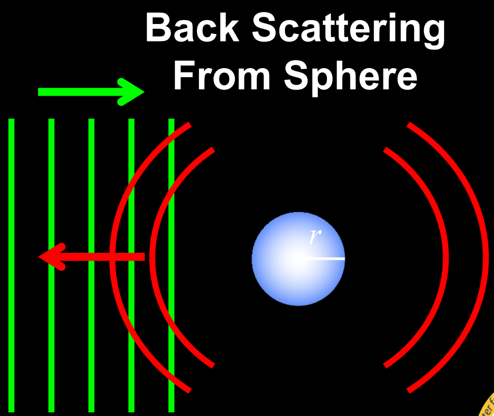


# Radar Return

- **Multiples effect of channel attenuation**
  - Transmitter to scatterer to receiver
  - $R_1^2$ $R_2^2$ loss for bistatic or $R^4$ loss monostatic
- **Consider cross section of sphere as reference target**
- **Three distinct regimes**
  - Rayleigh, $\sim r^6/\lambda^4$
  - Resonant
  - Optical

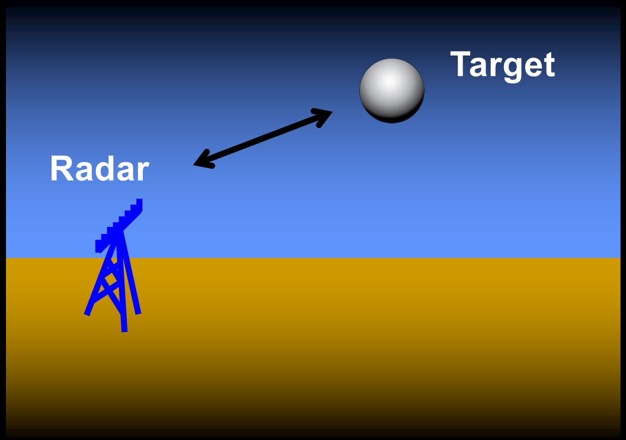


# Return Power

- **Consider constant illumination**
  - Monostatic radar
- **How much power is returned**
  - Power sent toward the target
    $P_t \, G_t$
  - Power flux at target
    $$\frac{P_t \, G_t}{4\pi \, r^2}$$
  - Target cross section (radiated back toward receiver)
    $$\sigma \Rightarrow \frac{P_t \, G_t}{4\pi \, r^2} \, \sigma$$
  - Power at receiver
    $$P_r = \frac{P_t \, G_t}{4\pi \, r^2} \, \sigma \, \frac{1}{4\pi \, r^2} A_{r,\mathrm{eff}} = \frac{P_t \, G_t}{4\pi \, r^2} \, \sigma \, \frac{1}{4\pi \, r^2} \, \frac{G_r \, \lambda^2}{4\pi}$$
    $$= \frac{P_t \, G_t \, G_r \, \lambda^2 \, \sigma}{(4\pi)^3 \, r^4}$$




**Gain-Effective Area Relationship**

$$G = 4\pi \frac{A_{\mathrm{eff}}}{\lambda^2}$$

# Coherent Versus Incoherent Integration

- **Signal model**
  - assume independent noise, $\underline{n}$

Samples of Received Signal Plus Noise

$$\underline{\mathbf{z}} = a\,\underline{\mathbf{s}} + \underline{\mathbf{n}}$$

Samples of Transmitted Signal

- **Consider energy at the output of matched filter**

$$E = \|\underline{\mathbf{z}}\,\underline{\mathbf{s}}^{\dagger}\|^2$$

- **Integrated SNR**

Expected Value

$$\mathrm{ISNR} = \frac{E_s}{E_n} = \frac{\langle \|a\,\underline{\mathbf{s}}\,\underline{\mathbf{s}}^{\dagger}\|^2 \rangle}{\langle \|\underline{\mathbf{n}}\,\underline{\mathbf{s}}^{\dagger}\|^2 \rangle}$$

Time-Bandwidth Product

- **Coherent integration of signal**

$$E_s = \langle \|a\,\underline{\mathbf{s}}\,\underline{\mathbf{s}}^{\dagger}\|^2 \rangle = P_r\, n_s^2 = P_r\, (TB)^2$$

- **Incoherent integration of noise**

$$E_n = \langle \|\underline{\mathbf{n}}\,\underline{\mathbf{s}}^{\dagger}\|^2 \rangle = P_n\, n_s = P_n\, (TB)$$

# Return SNR

- **Received target power**

$$P_r = \frac{P_t\, G_t\, G_r\, \lambda^2\, \sigma}{(4\pi)^3\, r^4}$$

- **Thermal noise at receiver**

$$P_n = k_B\, T_{\text{temp}}\, B\, f_n$$

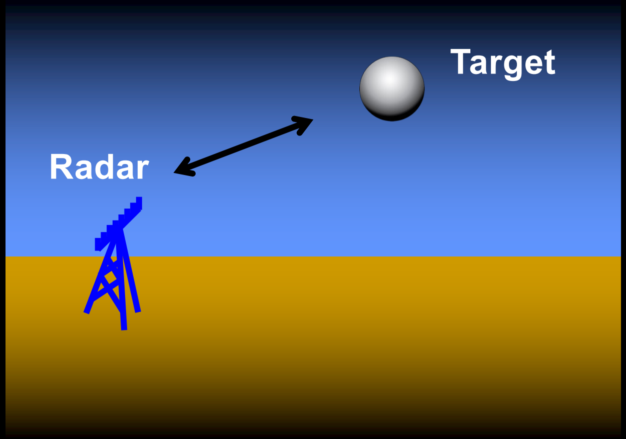
Noise Figure
Versus Noise Factor

- **SNR**

$$\text{SNR} = \frac{P_r}{P_n} = \frac{P_t\, G_t\, G_r\, \lambda^2\, \sigma}{(4\pi)^3\, r^4\, k_B\, T_{\text{temp}}\, B\, f_n}$$

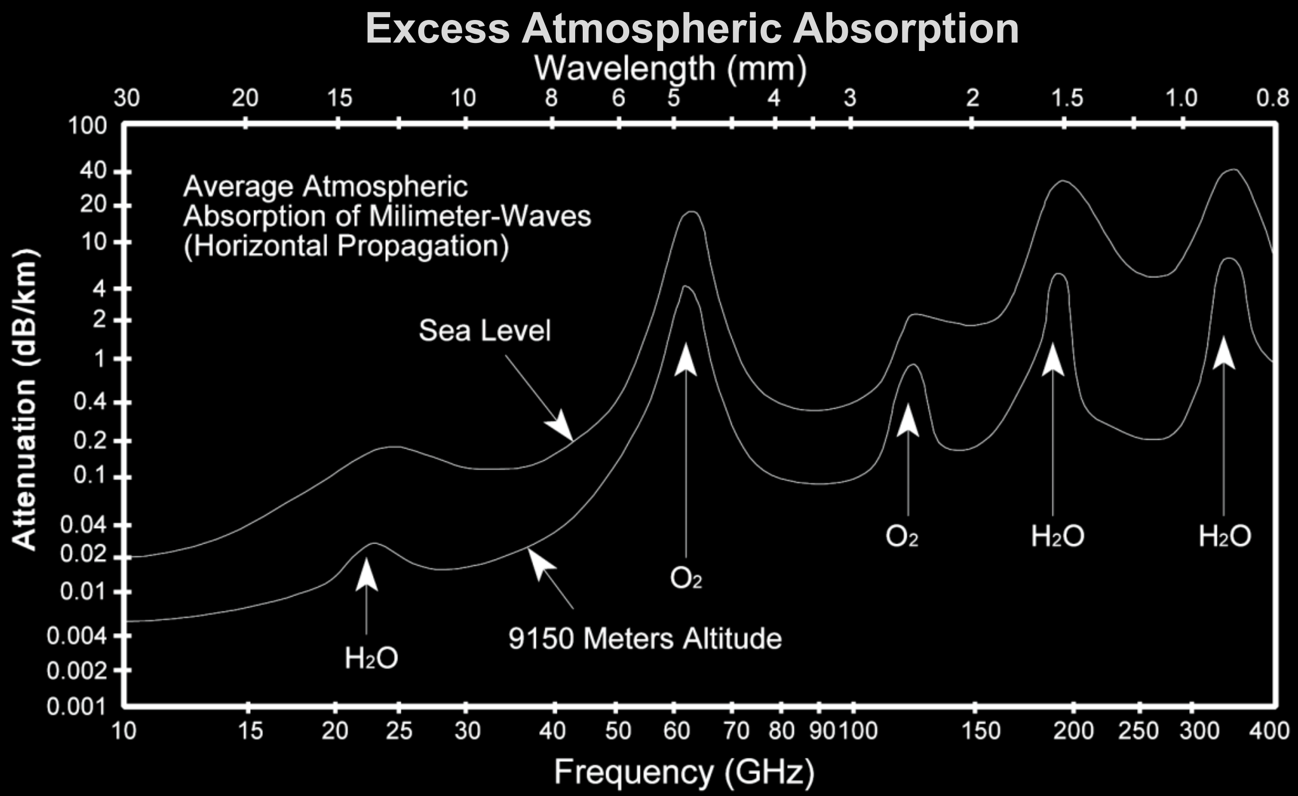
- **Integrated SNR**
  - Temporally and spectrally flat waveform

$$\text{ISNR} = T\, B\, \text{SNR} = T\, B\, \frac{P_t\, G_t\, G_r\, \lambda^2\, \sigma}{(4\pi)^3\, r^4\, k_B\, T_{\text{temp}}\, B\, f_n}$$



# “Line-of-Sight” Propagation

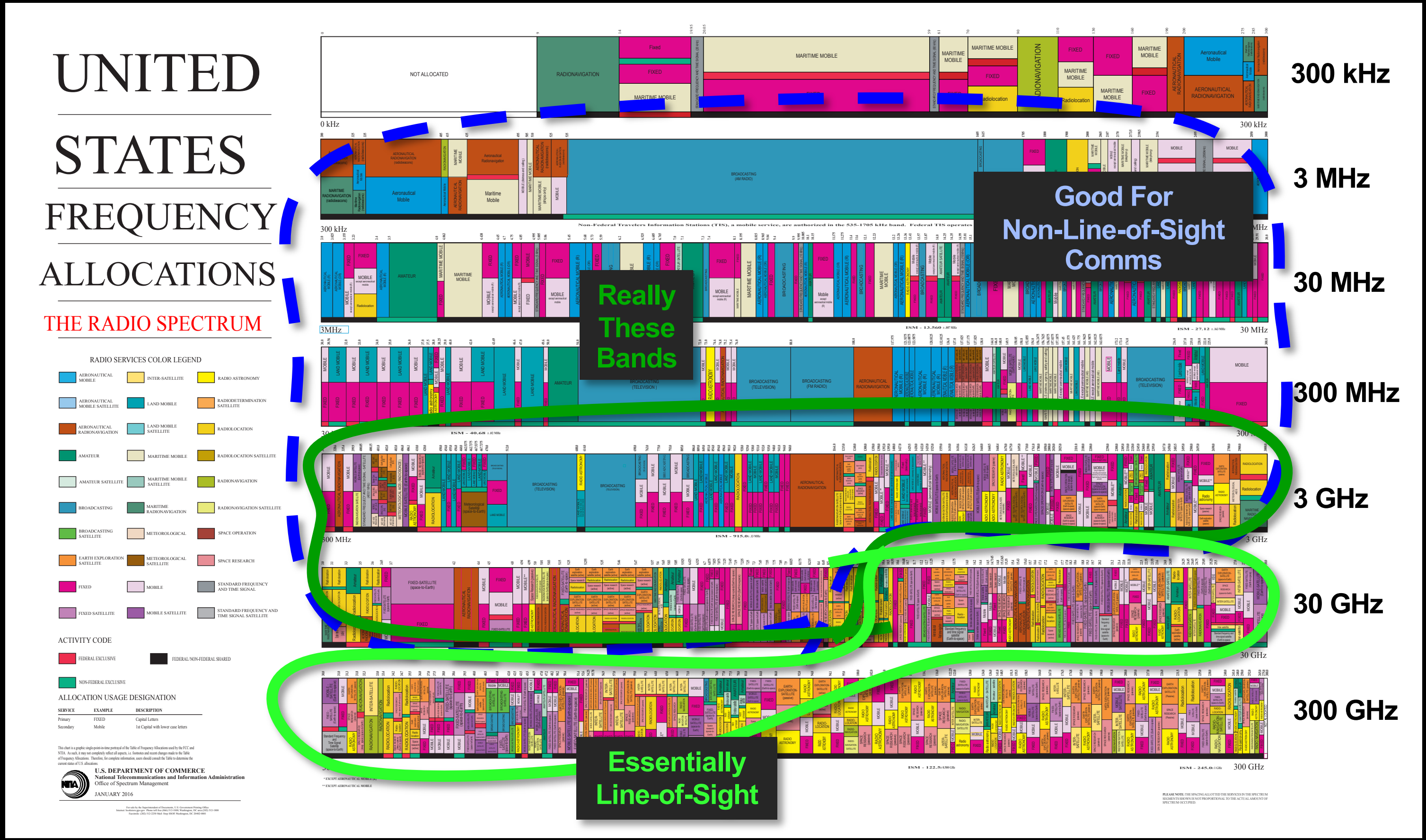
- Match spectrum to application
- Consider line-of-sight, range, bandwidth



# Not a Lot of Unused Spectrum

## *Ok, None*

- **Find spectrum to operate your system**
  - **Well, that escalated quickly**



# Doppler Frequency Shift

## *Special Relativity*

- **Consider the basic physics**
  - **Invoke special relativity**
  - **Time dilation**

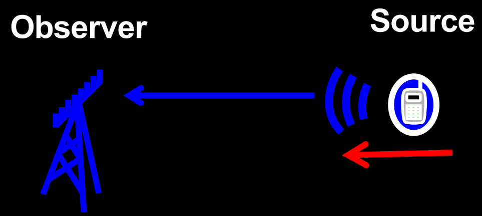
$$\lambda = c\,T_s - v\,T_s\,; \quad \text{Galilean transformation}$$

$$T_s = \frac{\lambda}{c - v} = \frac{1}{(1-\beta)\,f_s}\,; \quad \beta = \frac{v}{c}$$

$$T = \frac{T_s}{\gamma}\,, \quad \gamma = \frac{1}{\sqrt{1-\beta^2}}\,; \quad \text{time dilation}$$

$$f = \frac{1}{T} = \gamma\,(1-\beta)\,f_s = \frac{1-\beta}{\sqrt{(1-\beta)(1+\beta)}} f_s$$

$$= \sqrt{\frac{1-\beta}{1+\beta}} f_s$$




- **Do you need to worry about special relativity ($1000 \text{ m/s} >$ Mach 3)?**

$$f = \left[1 - \beta + \frac{\beta^2}{2} + O(\beta^3)\right] f_s$$

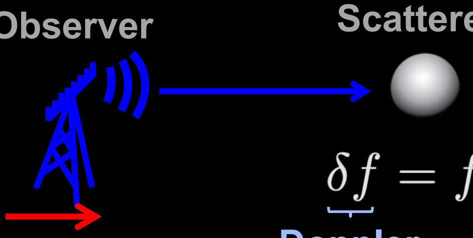
$$\beta = \frac{1000\,\text{m/s}}{3 \cdot 10^8\,\text{m/s}} \approx 3.3 \cdot 10^{-6}\,, \quad \frac{\beta^2}{2} = \frac{(1000\,\text{m/s})^2}{2\,(3 \cdot 10^8\,\text{m/s})^2} \approx 5.5 \cdot 10^{-12}$$

**Sufficiently Accurate Approximation**

$$\Delta f_{\text{Doppler}} \approx \frac{v}{c} f_s$$

# Radar Doppler Frequency

- **Doppler frequency of monostatic radar is twice standard Doppler shift**
- **Easier to see if you think of a moving radar and static target**

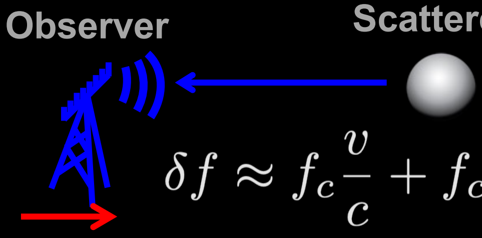



$$\underbrace{\delta f}_{\text{Doppler Shift}} = f_c \frac{v}{c}$$

Doppler Shift

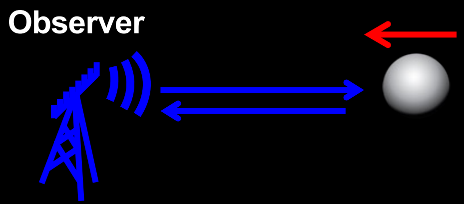
Center Frequency

Fraction of Speed of Light




$$\delta f \approx f_c \frac{v}{c} + f_c \frac{v}{c}$$

- **More precisely**
  - Assume short pulses
  - Assume monostatic
  - Assume $v$ is small




$$\phi_1 = 2\pi\, f_c\, t_1 = 2\pi\, f_c\, (2R/c)$$

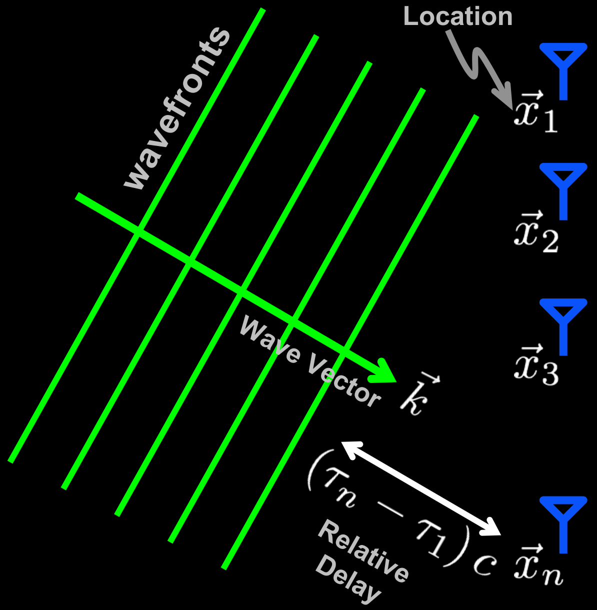
$$\phi_2 = 2\pi\, f_c\, t_2 = 2\pi\, f_c\, (2[R + v\, \text{PRI}]/c)$$

$$\delta f = \frac{\phi_2 - \phi_1}{2\pi\, \underbrace{\text{PRI}}} = f_c\, \frac{2v}{c}$$

Pulse Repetition Interval

# Antenna Arrays

- **Phase multiple antenna elements to control direction of transmitted or received power**
- **Narrowband model - can't resolve antennas,** $B \ll \frac{c}{\|\mathbf{x}_1 - \mathbf{x}_n\|}$




$$s(t-\tau) \approx a\,u(t)\,e^{i\,\mathbf{k}\cdot\mathbf{x}_1}$$

$$s(t-\tau) \approx a\,u(t)\,e^{i\,\mathbf{k}\cdot\mathbf{x}_2}$$

$$s(t-\tau) \approx a\,u(t)\,e^{i\,\mathbf{k}\cdot\mathbf{x}_3}$$

$$\vdots$$

$$s(t-\tau) \approx a\,u(t)\,e^{i\,\mathbf{k}\cdot\mathbf{x}_n}$$

Baseband Signal

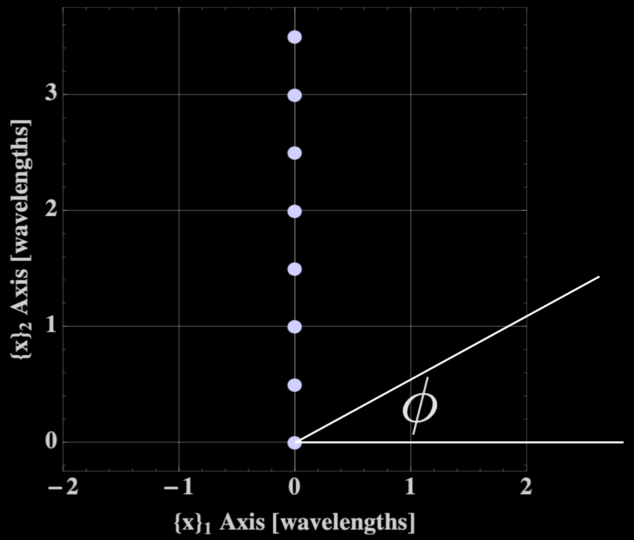
Complex Baseband Representation

$$= a\,u(t)\,\boxed{\mathbf{v}(\mathbf{k};\mathbf{x}1,\cdots,\mathbf{x}_n)}$$

Steering Vector

# Angle-of-Arrival Estimation

- **Determine angle to source based upon observed phase on antennas**
  - Lots of pseudo-spectrum techniques
  - Often associated with maximizing inner product between observation and model: $\vec{v}^\dagger \, \vec{z}$




- **Consider simple spatial model**
  - Array response "steering" vector

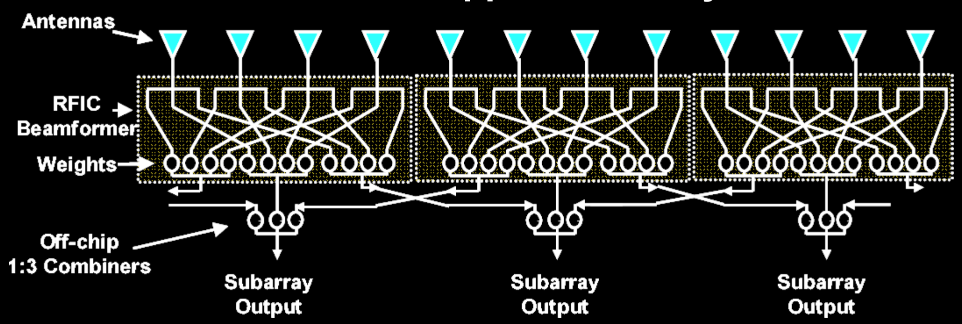
$$\vec{v}(\vec{k};\vec{x}_1,\cdots,\vec{x}_n)=\begin{pmatrix} e^{i\,\vec{k}\cdot\vec{x}_1} \\ e^{i\,\vec{k}\cdot\vec{x}_2} \\ \vdots \\ e^{i\,\vec{k}\cdot\vec{x}_n} \end{pmatrix}=\begin{pmatrix} e^{i\,\|\vec{k}\|\,\sin(\phi)\,0\,\lambda/2} \\ e^{i\,\|\vec{k}\|\,\sin(\phi)\,1\,\lambda/2} \\ \vdots \\ e^{i\,\|\vec{k}\|\,\sin(\phi)\,(n-1)\,\lambda/2} \end{pmatrix}=\begin{pmatrix} e^{i\,\pi\,\sin(\phi)\,0} \\ e^{i\,\pi\,\sin(\phi)\,1} \\ \vdots \\ e^{i\,\pi\,\sin(\phi)\,(n-1)} \end{pmatrix}$$

- **Note: no one actually uses 1/2 wavelength space because antennas (or subarrays) have gain, so a larger spacing is employed**

# “Real” Antenna Arrays

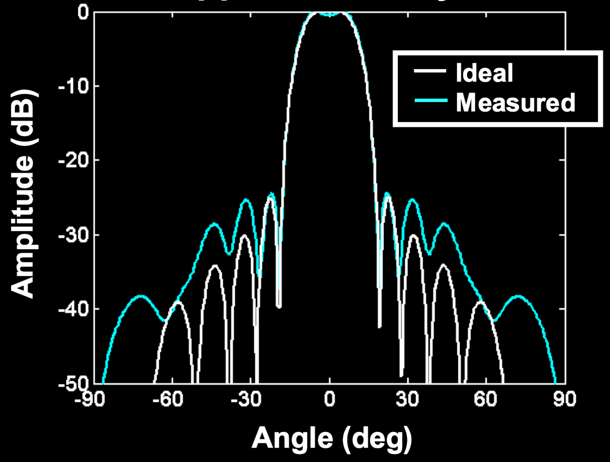
- Reduce number of adapted phase centers by using subarrays
  - Hybrid approach
- Overlap subarrays to reduce sidelobes
- Employ true time-delay steering for large wideband scenarios
  - Space-Time beamforming
- Observe same pattern for transmit and receive because of reciprocity

**Overlapped Subarrays**

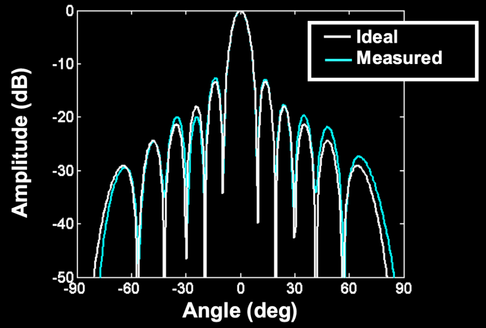



S. Duffy, D. D. Santiago, J. Herd, “Design of overlapped subarrays using an RFIC beamformer”,, IEEE Antennas and Propagation Society International Symposium, 2007

**Overlapped Subarray Pattern**




**Reference Pattern**



# MuSiC
## Multiple Signal Classification

- **Estimate angle of incoming signal**
  - Common approach is MuSiC
    - Inverse of norm squared of steering vector projected onto noise subspace

**Psuedospectrum**

$$P_{\text{music}}(\phi) = \frac{\mathbf{v}^\dagger(\phi)\,\mathbf{v}(\phi)}{\mathbf{v}^\dagger(\phi)\,\mathbf{P}_{\text{noise}}\,\mathbf{v}(\phi)}$$

**Projection Operator**

$$\mathbf{P}_{\text{noise}} = \sum_{m \in \mathcal{S}_{\text{noise}}} \mathbf{e}_m\,\mathbf{e}_m^\dagger$$

- **Decompose covariance matrix into eigen signal and noise subspaces**

$$\mathbf{R} = \underbrace{\sum_{m=1}^{n_{noise}} \lambda_m\,\mathbf{e}_m\,\mathbf{e}_m^\dagger}_{noise} + \underbrace{\sum_{m=n_{noise}+1}^{n_r} \lambda_m\,\mathbf{e}_m\,\mathbf{e}_m^\dagger}_{signal}$$

$$n_{noise} = \max\{m : \lambda_m \leq \text{threshold}\}$$

Noise Projection Operator

$$\left\{\ \mathbf{P} = \sum_{m \in noise} \mathbf{e}_m\,\mathbf{e}_m^\dagger\right.$$

- **Model signal as ideal array response**

$$\mathbf{P}_{\text{signal}} = \frac{\mathbf{v}_0\,\mathbf{v}_0^\dagger}{\mathbf{v}_0^\dagger\,\underbrace{\mathbf{v}_0}}$$

$$\mathbf{P}_{\text{noise}} = \mathbf{I} - \mathbf{v}_0\,(\mathbf{v}_0^\dagger\,\mathbf{v}_0)^{-1}\,\mathbf{v}_0^\dagger$$

True Steering Vector

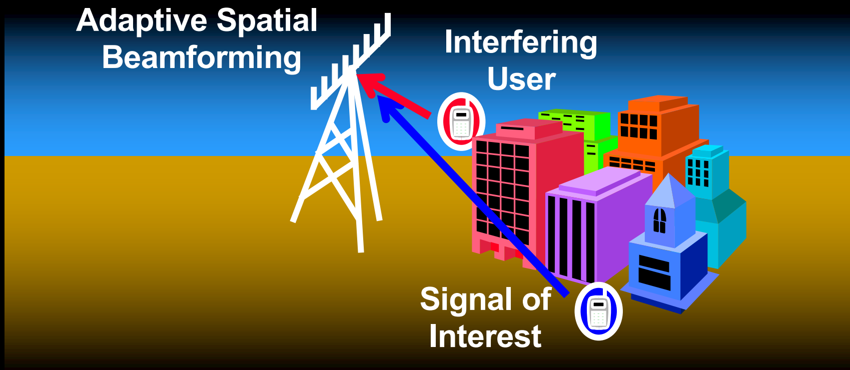
  - Music psuedospectrum

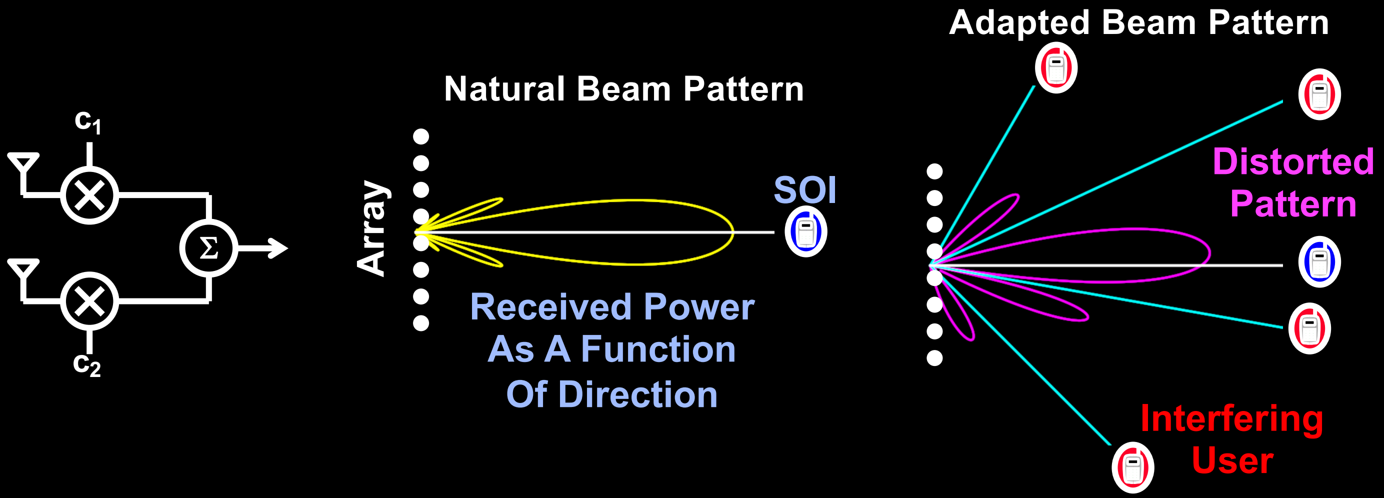
$$\begin{aligned} P_{\text{music}}(\phi) &= \frac{\mathbf{v}^\dagger(\phi)\,\mathbf{v}(\phi)}{\mathbf{v}^\dagger(\phi)\,\mathbf{P}_{\text{noise}}\,\mathbf{v}(\phi)} \\ &= \frac{n}{\mathbf{v}^\dagger(\phi)\,[\mathbf{I} - \mathbf{v}_0\,(\mathbf{v}_0^\dagger\,\mathbf{v}_0)^{-1}\,\mathbf{v}_0^\dagger]\,\mathbf{v}(\phi)} \\ &= \frac{1}{\left[1 - \left\|\frac{\mathbf{v}^\dagger(\phi)\,\mathbf{v}_0}{n}\right\|^2\right]} \end{aligned}$$

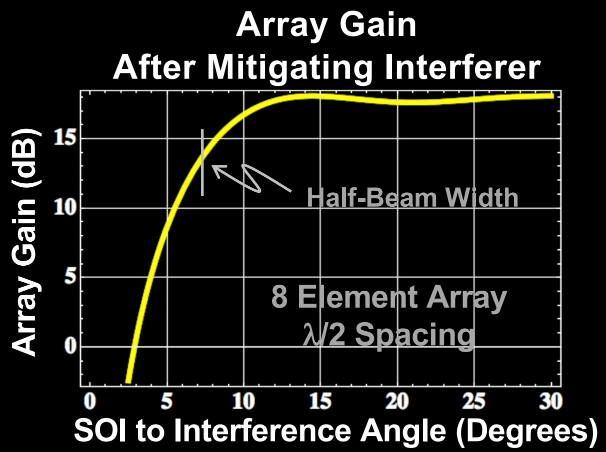
$$1 \leq P_{\text{music}}(\phi) \leq \infty$$

# Adaptive Antenna Array Processing
## *Spatial Interference Cancellation*

- Focus on user of interest while nulling interference from other users
- Adapt antenna array beam pattern
  - Beat received signal at each antenna against others
  - Beam pattern adapted for each user simultaneously



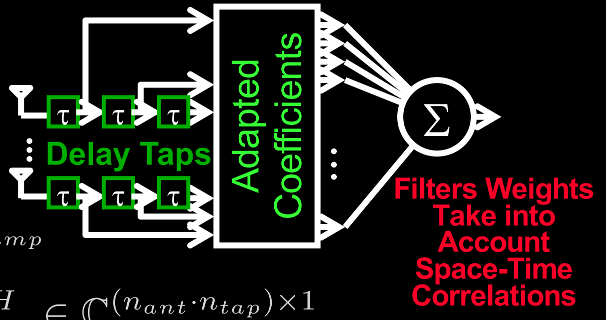



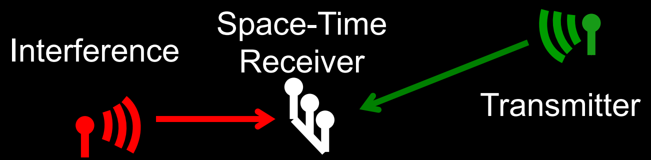

D. W. Bliss and S. Govindasamy, "Adaptive Wireless Communications: MIMO Channels and Networks," Cambridge University Press, Cambridge, 2013.

# 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**




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

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

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

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

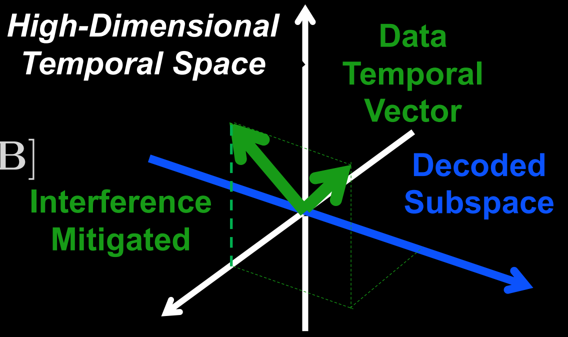
**Temporal Mitigation**

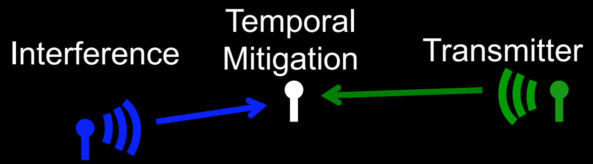
Projects onto Space Orthogonal to Known Interference Sequence

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

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

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



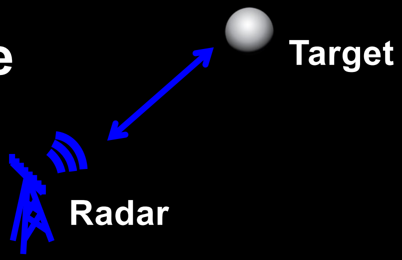





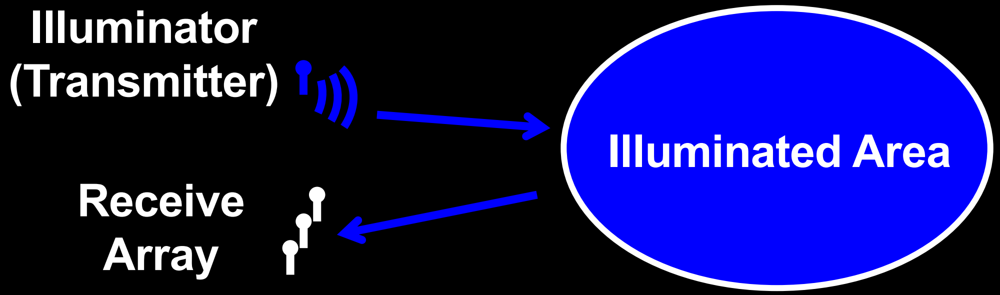

D. W. Bliss and S. Govindasamy, “Adaptive Wireless Communications: MIMO Channels and Networks,” Cambridge University Press, Cambridge, 2013.

# Radar Angle Estimation

- Estimate range, Doppler frequency, and angle
  - Focus on range and Doppler frequency, here

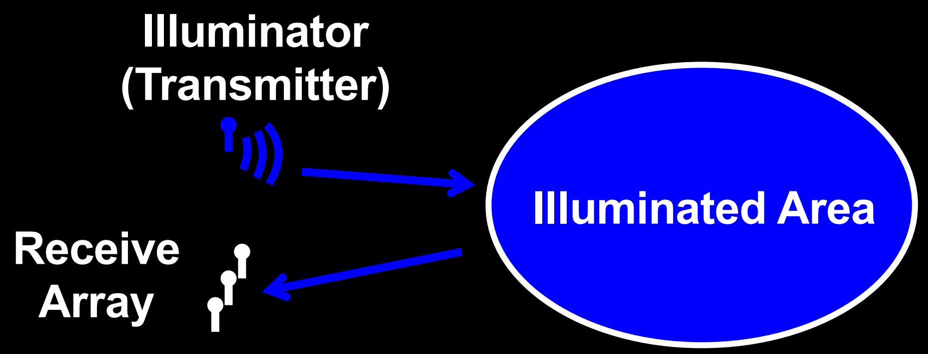



- Employ multiple phase centers
  - Angle information is encoded in the relative phase of the antennas
    - Narrowband assumption



# Simple Radar Received Signal Model

- **Illumination has pattern**
  - Range dependent
    - Propagation
    - Antenna pattern




- **Angle information encoded in relative phase**

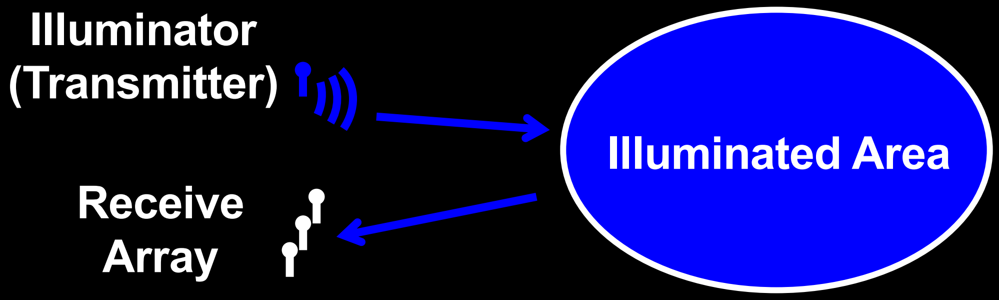
$$\mathbf{z}(t) = \sum_m a(\phi_m, r_m)\, \mathbf{v}(\phi_m)\, s(t - \tau_m) + \mathbf{n}(t)$$

$$\underbrace{\mathbf{v}(\phi_m)}_{\text{Steering Vector}} = \begin{pmatrix} e^{i\, \mathbf{k}_m \cdot \mathbf{x}_1} \\ e^{i\, \mathbf{k}_m \cdot \mathbf{x}_2} \\ \cdots \\ e^{i\, \underbrace{\mathbf{k}_m}_{\text{Wave Vector}} \cdot \mathbf{x}_{n_r}} \end{pmatrix} = \begin{pmatrix} e^{i\, \frac{2\pi}{\lambda}\, \sin\phi_m\, x_1} \\ e^{i\, \frac{2\pi}{\lambda}\, \sin\phi_m\, x_2} \\ \cdots \\ e^{i\, \frac{2\pi}{\lambda}\, \sin \underbrace{\phi_m}_{\text{Physical Angle}}\, x_{n_r}} \end{pmatrix}$$

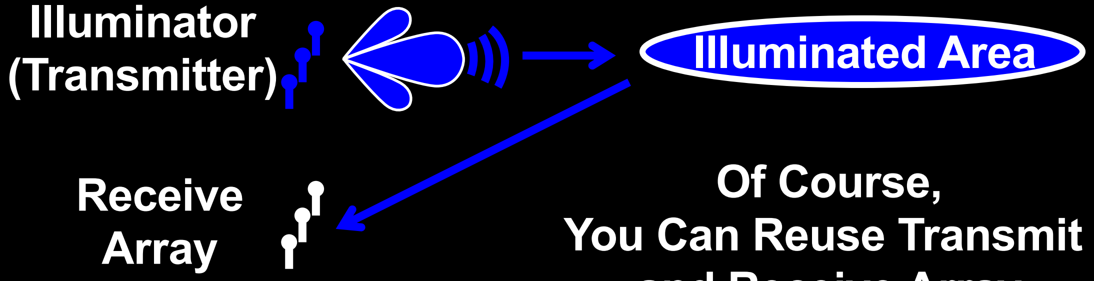
Considering Simple Linear Array

# Radar Transmit Pattern

- Illuminate from single element

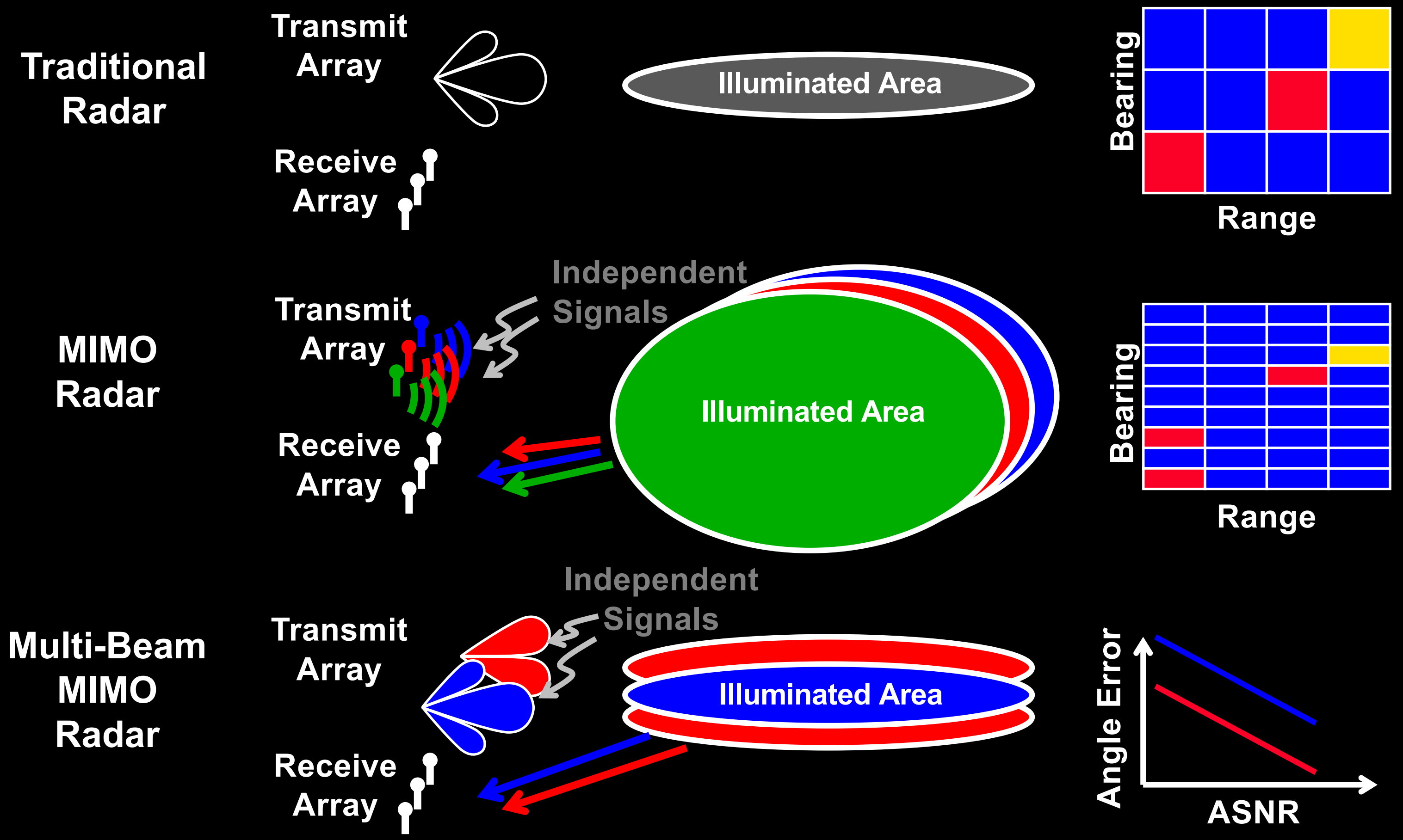



- Illuminate from beamformer



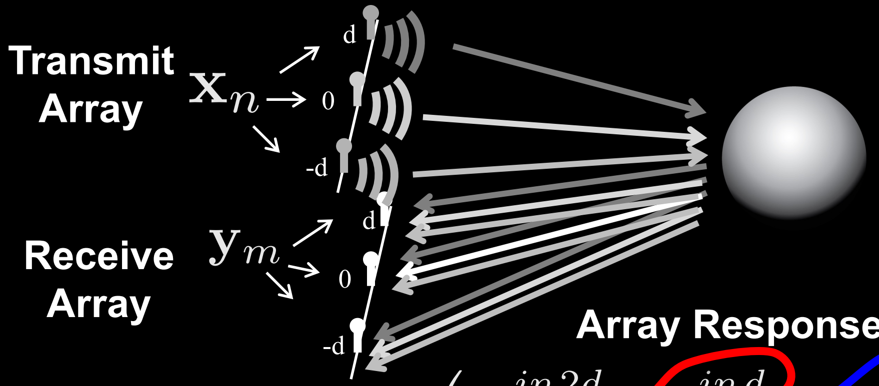

Of Course,
You Can Reuse Transmit
and Receive Array

# MIMO versus Traditional Coherent Radar



# MIMO Radar Channel

## Concept of Virtual Array

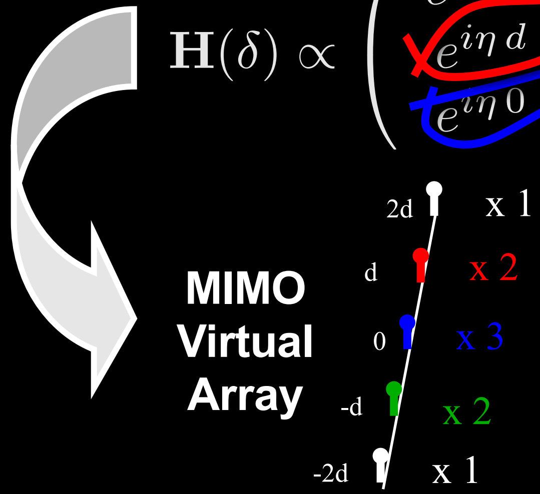



### Notional Model

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

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

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




- **Channel estimate provides estimate of MIMO virtual array**
- **Virtual array may over-represented elements**
  - Convolution of real arrays produces virtual array
  - Suggesting sparse arrays

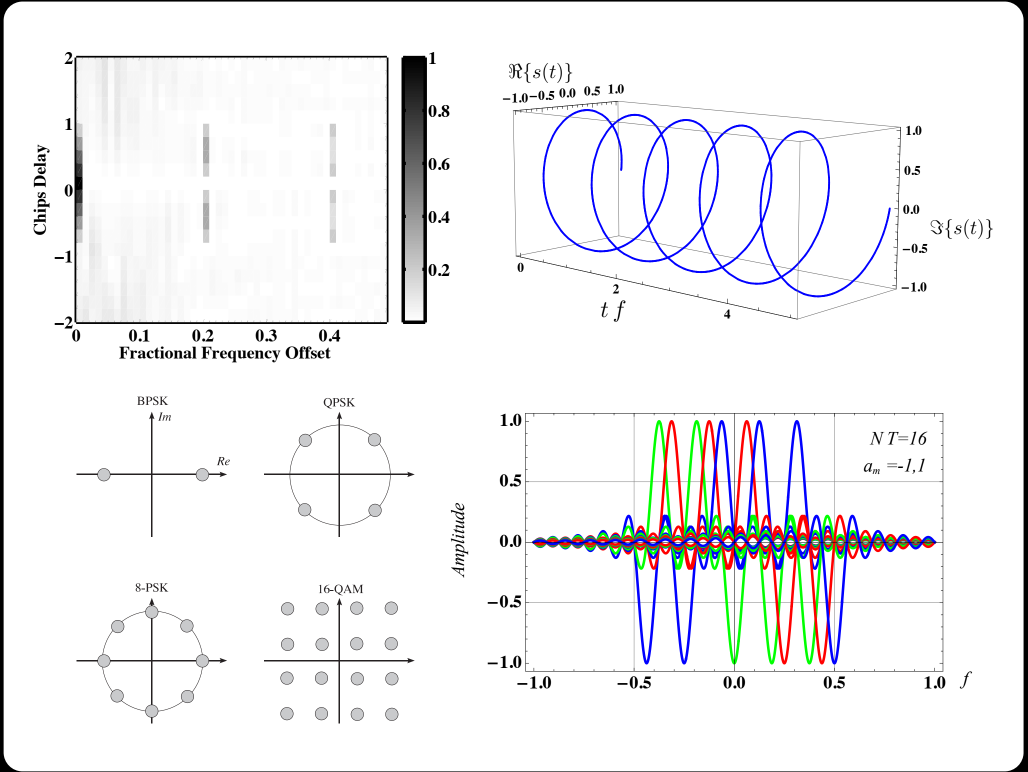
# Waveform Issues

## Radar Goals

- Desire constant modulus
  - Small peak-to-average power ratio (PAPR)
- Want good complex ambiguity function
  - Large bandwidth
  - Range ambiguities bad
  - Doppler is less clear

## Communications Goals

- Make dispersion compensation easy
  - OFDM is popular
- Use convenient modulation
  - Match spectral efficiency needs
- Employ convenient coding and acknowledgement frames

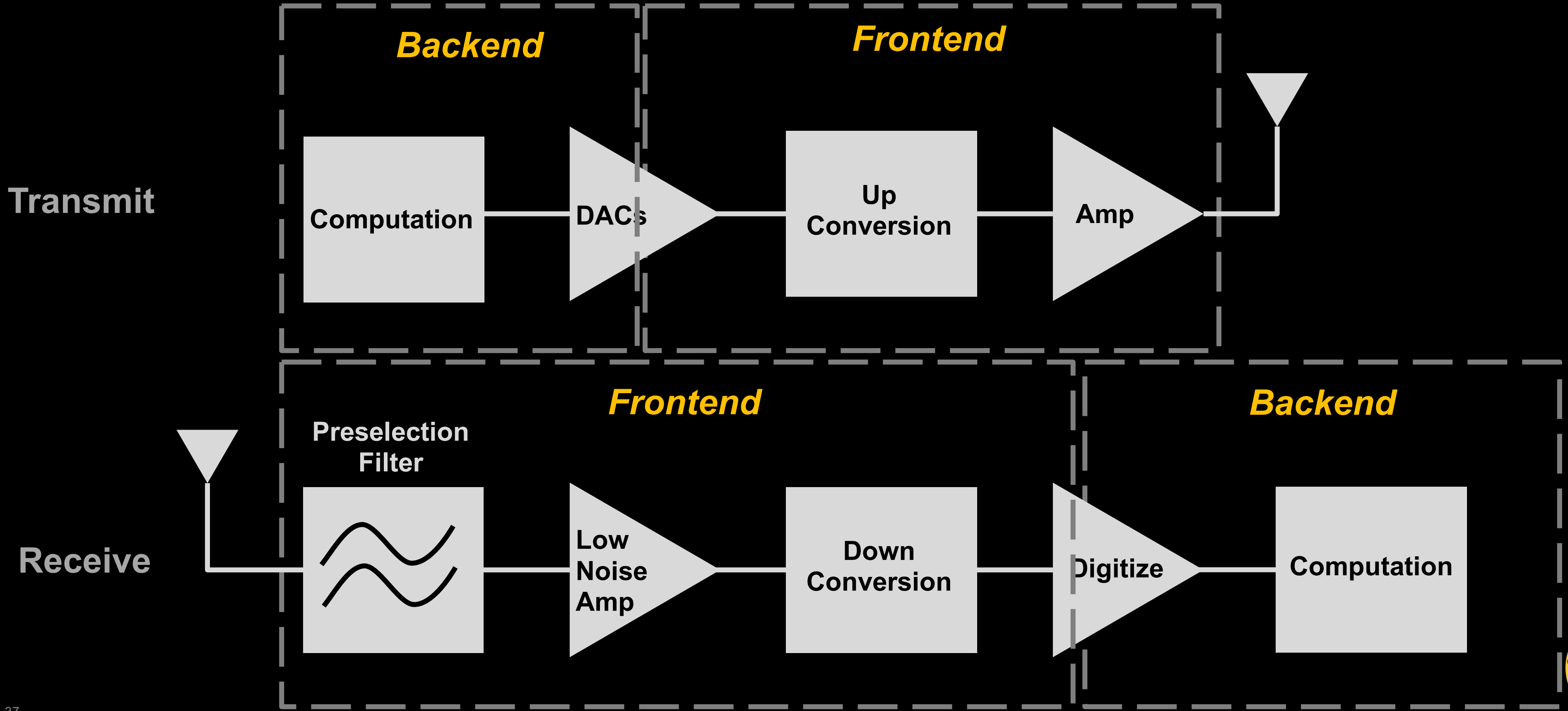


# How Do We Get There?

- Review Goals and Implications of Heilmeier Questions
- Underlying Physics of Applications
- Explore New Enabling Technologies
- Explore Metrics of Performance
- Investigate Examples

# Simple Model of an RF System

- Simplify system to an embarrassing extent
- Identify frontend and backend of system

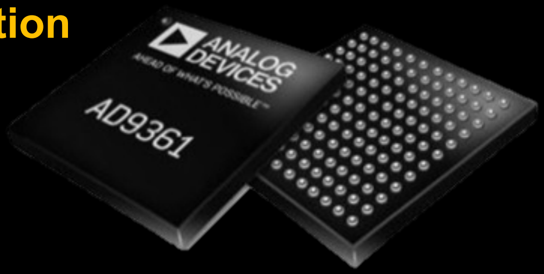


# Novel Flexible Frontends

- Dynamically match spectral use to use
  - Requirements and Environments
- Provide flexible spectral access in presence of in-band or nearby interference
- Reduce need for preselection filters
  - Sensitivity to near-band interference

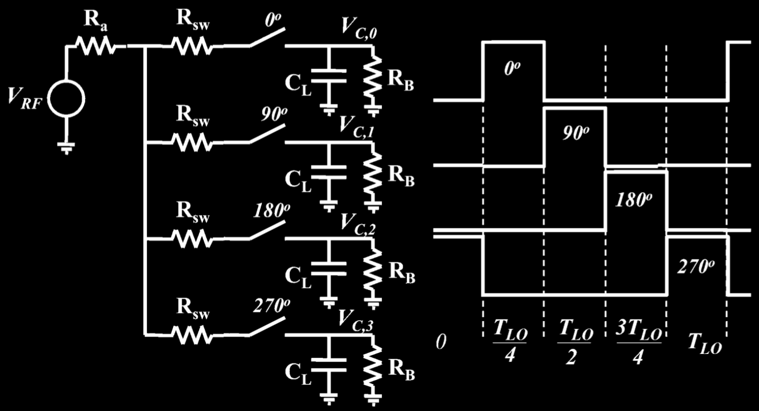
Commercial transceiver up/down-conversion and digitization

AD RF Transceiver Technology

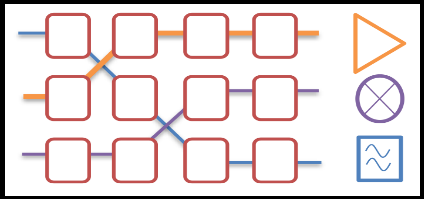


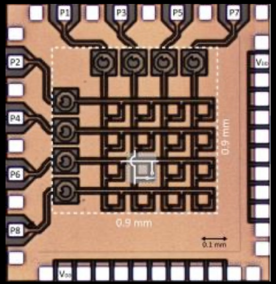

Novel Approaches

Polyphase Mixer




Truly Flexible Frontends
DARPA RF-FPGA

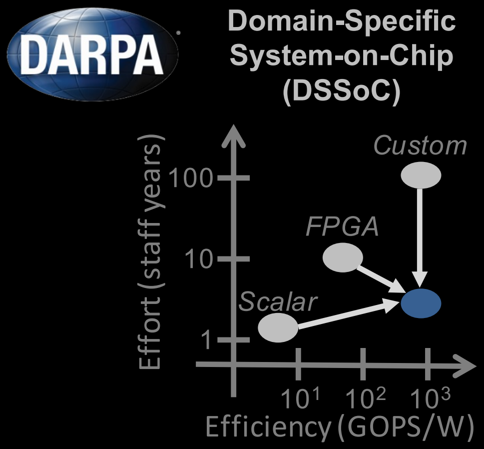


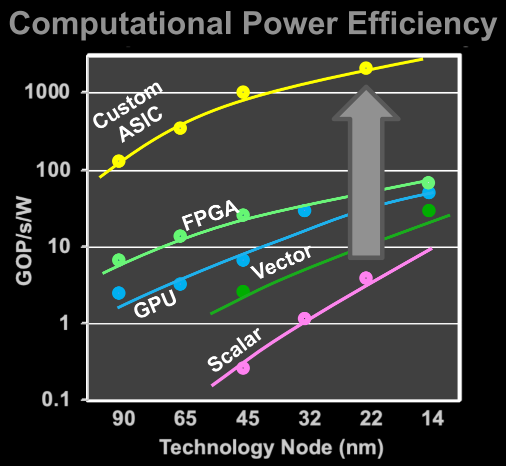


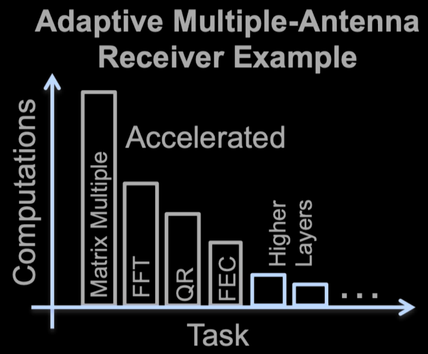
# Reinvent Processor Technology

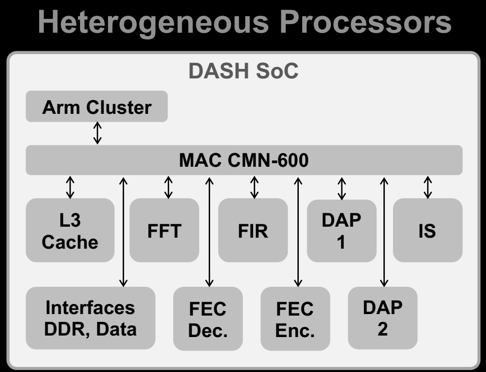
***D**omain-Focused **A**dvanced **S**oftware-Reconfigurable **H**eterogeneous **SoC***

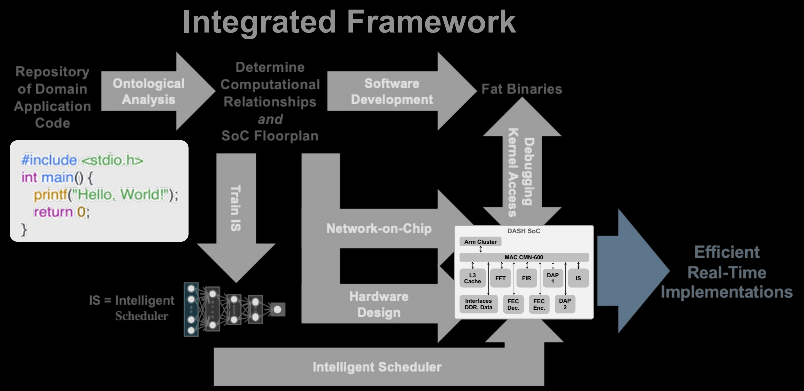
- **Enable flexible RF systems**
- **Leverage and extend next-generation flexible computational architectures**
  - **Coarse-scale heterogeneous processors**
- **Simplify use by employing advanced on-chip intelligence and software support**




*Prime*

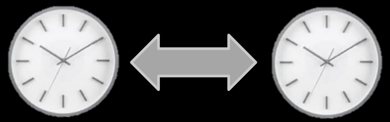
https://www.youtube.com/watch?v=Z6yDE3TbhcU&t=2620s

Arizona State University · arm · Collins Aerospace · General Dynamics Mission Systems · The University of Arizona · University of Michigan · The University of Texas at Austin · Wisconsin · DASH Tech IC · WISCA

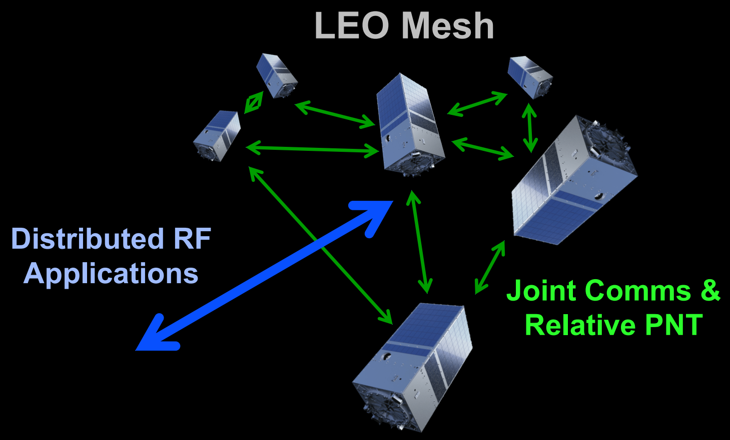
# Enabling Novel Distributed RF

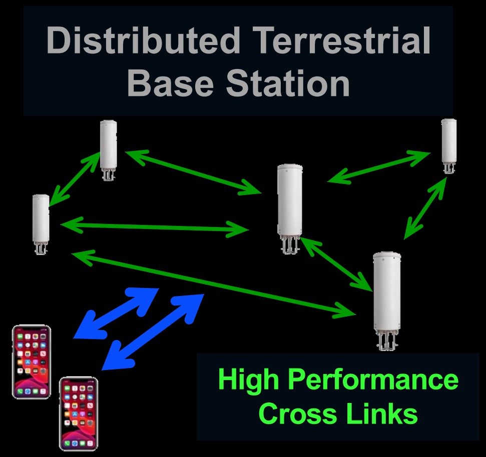
- **Develop distributed coherent systems**
  - Distributed space-time transmit and receive beamforming
- **Employ intra-mesh links for precise (phase-accurate) time exchange and data distribution**

Distributed Coherence



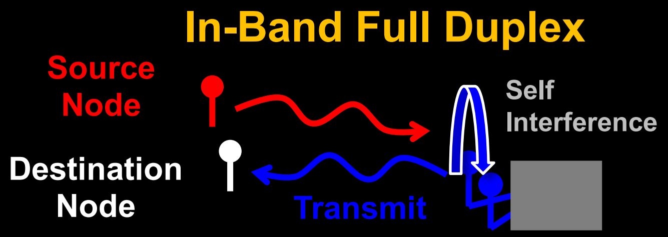
- **Enable new functionality by employing sparse mesh of radios**
  - Enable communications in contested RF environments
  - Increase transmit power (~ data rate): $N^2$
  - Increase receive SNR: N
  - Enabling new class of precise multistatic radar systems
- **Requires phase-accurate distributed coherence between radios**



# In-Band Full Duplex

- **Leverage growing technological base for simultaneous transmit and receive**
  - Same time and frequency
  - Easy in principle, insanely difficult in practice
  - Need more than 100 dB of suppression
- **Potentially increase throughput by transmitting and receiving at same time**
- **Enables mix of signaling needs**
  - Communications versus sensing
  - Example: using communications signal as monostatic radar




- **Mitigate "known" signal**
- **Compensate for unknown, potentially dynamic channel**
  - Mildly dispersive
  - Mildly nonlinear
  - Everything matters

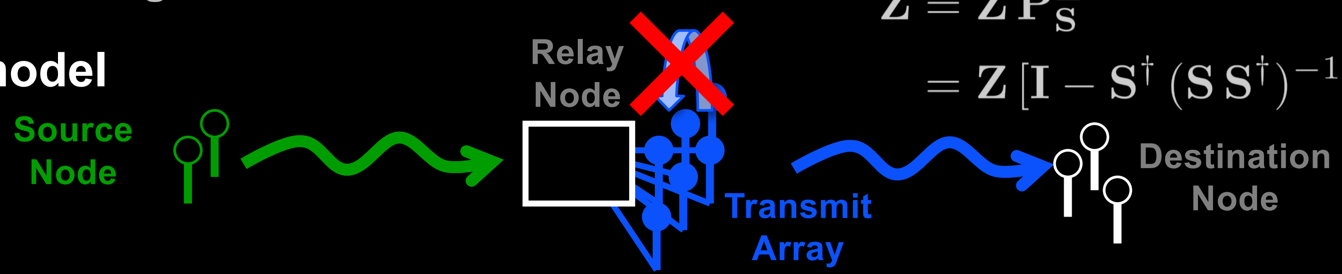
# In-Band Full-Duplex Challenges

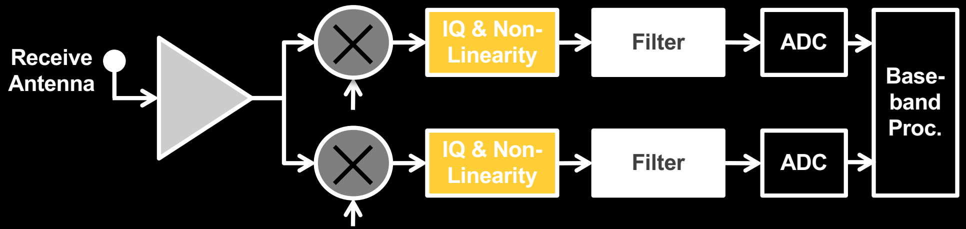
- **Employ in-band full-duplex signaling**
  - Same time and frequency
  - Multiple layers of interference mitigation
- **Consider simple system model**
- **Consider one of many complications**
  - Mild receive nonlinearities
  - IQ Mismatch

**Total Isolation = Spatial Isolation + Processing**
**Total Goal > 100dB**

Temporal Mitigation

$$\tilde{\mathbf{Z}} = \mathbf{Z}\,\mathbf{P}_{\mathbf{S}}^{\perp} = \mathbf{Z}\,[\mathbf{I} - \mathbf{S}^{\dagger}\,(\mathbf{S}\,\mathbf{S}^{\dagger})^{-1}\,\mathbf{S}]$$




Self-Interference Channel

Baseband Signal

IQ Mismatch

$$z(t) = \Re\{h\,x(t)\} + i\,\Im\{h\,x(t)\}\,(1+\varepsilon) - \frac{\alpha_{\Re}}{\sigma_{\text{rx}}^2}(\Re\{h\,x(t)\})^3 - i\,\frac{\alpha_{\Im}}{\sigma_{\text{rx}}^2}(\Im\{h\,x(t)\})^3 - \mathcal{O}(h\,x(t))^5 + n(t)$$


A. Sabharwal, P. Schniter, D. Guo, D. W. Bliss, S. Rangarajan and R. Wichman, "In-Band Full-Duplex Wireless: Challenges and Opportunities," IEEE Journal on Selected Areas in Communications, Sept. 2014.
D. W. Bliss, P. A. Parker and A. R. Margetts, "Simultaneous Transmission and Reception for Improved Wireless Network Performance," IEEE Workshop on Statistical Signal Processing, 2007.

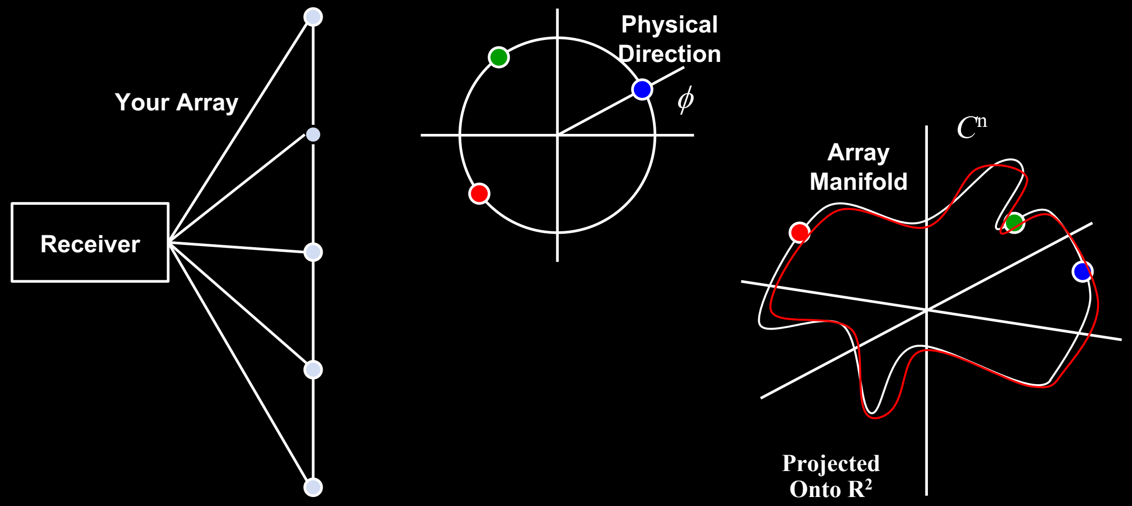
# When You Don’t Know the Answer, Invoke ML

- Use ML to approximate high-dimensional nonlinear functions
  - Wide range of recent advances in parameter estimation and processing
  - Applicable to wide range of nonlinear functions
    - D. Elbrächter, D. Perekrestenko, P. Grohs, H, Bölcskei, “Deep neural network approximation theory,” IEEE Transactions on Information Theory, 2021

- Understand implications of model mismatch
  - “Currently, artificial intelligence (AI) is remarkably stupid, sometimes useful, but stupid. It is important to remember that machine learning (ML), which presently is most of AI, is just "curve fitting" in a high-dimensional space that you cannot visualize using basis functions that you cannot understand. ML itself has no actual understanding. Furthermore, without serious analysis of ML's robustness and interpretability, you have no chance of knowing if what it produces is valid or good-looking lies. Basic theory on ML robustness and interpretability is still very weak. You have been warned.” – Dan Bliss

# Interesting ML Applications

- **Identify the right applications**
  - Resource optimization
    - Approximate full searches
    - Much faster than traveling salesperson search
  - Manifold learning
    - Antenna array calibration, particularly in complicated environments
    - Connect to partial physical knowledge



# How Do We Get There?

- Review Goals and Implications of Heilmeier Questions
- Underlying Physics of Applications
- Explore New Enabling Technologies
- **Explore Metrics of Performance**
- Investigate Examples

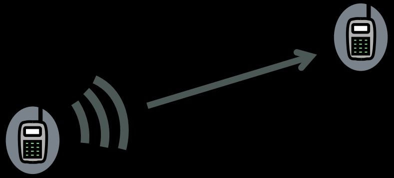
# What Are We Doing?

- Move information
- Detect states or objects
- Estimate parameters
- Track parameter evolution
- Operate in presence of noise

**Drives Us to Explore Detection and Estimation Theory**

# Communications Information Bound

- **Move bits from one place to another**
- **Specify model**
  - Amplitude domain



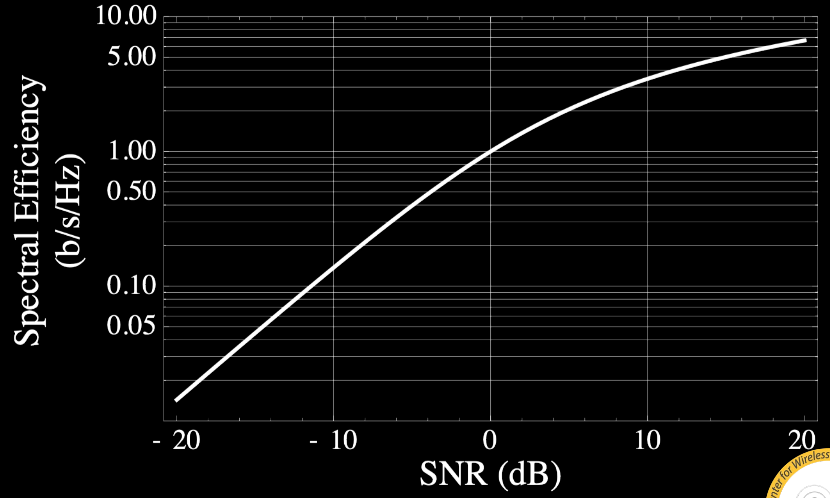
$$\underbrace{z(t)}_{\text{Received Signal}} = \overbrace{a}^{\text{Attenuation}}\,\underbrace{s(t)}_{\text{Transmitted Signal}} + \overbrace{n(t)}^{\text{Noise}}$$

- **Identify limits to performance**
  - Ratio of signal power to noise power is key
  - Known as channel capacity or Shannon Limit

$$\underbrace{C}_{\text{Channel Capacity (b/s)}} \leq \overbrace{B}^{\text{Total Bandwidth}} \log_2(1 + \overbrace{\text{SNR}}^{\text{SNR} = \frac{P_{\text{signal}}}{P_{\text{noise}}}})$$

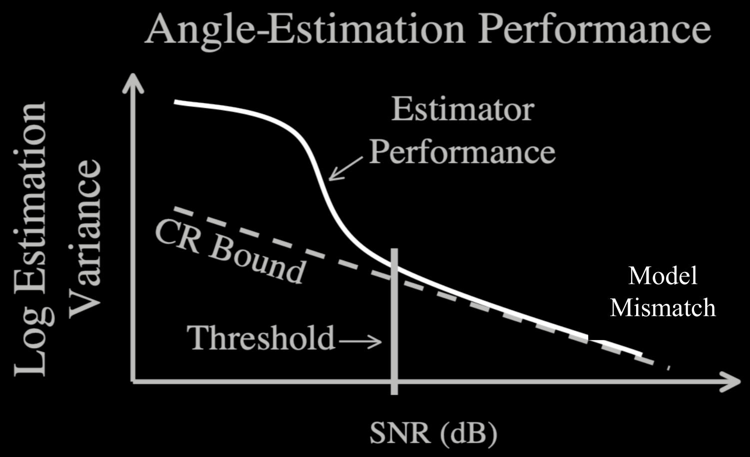
  - Spectral efficient is C/B

**Shannon Limit**



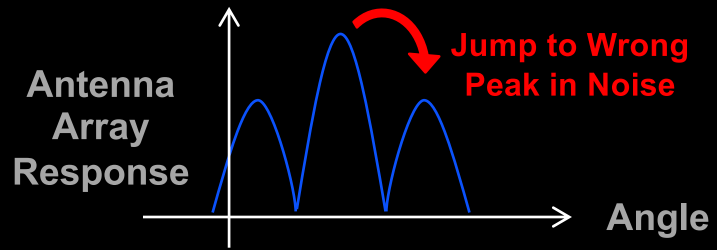
# Parameter Estimation Performance

- **Performance of estimator as a function of**
  - **SNR**
  - **Integrated SNR**




- **Typical estimator performance**
  - **Asymptotic region**
  - **Transition region**
  - **Random region**

- **Above some threshold point "good" estimator performance approaches Cramer-Rao bound**
  - **Cramer-Rao ignores large errors**
  - **Nonlocal error bounds exist (Weiss-Weinstein, Method of Interval Errors)**



# Estimator Variance

- **Consider random variable**

$$x \sim \underbrace{p(x;\theta)}$$

Probability Density Function

- **Assume single parameter of interest**

$$\theta$$

- **Estimator of parameter based on sequence of observations**

$$\hat{\theta} = f(x_1, x_2, x_3, \cdots)$$

- **Variance of estimatation**

$$\begin{aligned} \text{var}(\hat{\theta}) &= \left\langle (\hat{\theta} - \theta)^2 \right\rangle \\ &= \int dx\, (\hat{\theta} - \theta)^2\, p(x;\theta) \end{aligned}$$

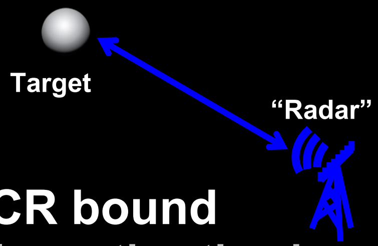
**Note:**
***Do Not Confuse Signal Variance with Parameter Estimation Variance***

# Cramer-Rao Bound

## *Model*

- **Radar estimates range and Doppler of target**
  - Simple universe
  - Nonfluctuating target (signal in the mean)

**Radar Model**




$$r = \frac{c}{2}\,\tau$$

$$\begin{aligned} z(t) &= b\, s(t-\tau) + n(t) \\ &= \underbrace{a}\, e^{i\overbrace{\phi}}\, s(t - \underbrace{\tau}) + n(t) \end{aligned}$$

Parameters

- **Multivariate CR bound**
  - Evaluate delay estimation bound and convert to range

$$\begin{aligned} \mathrm{cov}\{\hat{\boldsymbol{\theta}}\} &= \left\langle (\hat{\boldsymbol{\theta}} - \boldsymbol{\theta})(\hat{\boldsymbol{\theta}} - \boldsymbol{\theta})^T \right\rangle \\ &\geq \underbrace{\mathbf{J}^{-1}} \end{aligned}$$

Inverse of Fisher Information Matrix

$$\begin{aligned} \{\mathbf{J}\}_{m,n} &= \left\langle \left( \frac{\partial}{\partial\{\boldsymbol{\theta}\}_m} \log p(\mathbf{z};\boldsymbol{\theta}) \right) \left( \frac{\partial}{\partial\{\boldsymbol{\theta}\}_n} \log p(\mathbf{z};\boldsymbol{\theta}) \right) \right\rangle \\ &= -\left\langle \frac{\partial^2 \log p(\mathbf{z};\boldsymbol{\theta})}{\partial\{\boldsymbol{\theta}\}_m\, \partial\{\boldsymbol{\theta}\}_n} \right\rangle \end{aligned}$$

# Model

- **Three parameters**
  - Delay
  - Amplitude
  - Phase

$$z(t) = b\, s(t-\tau) + n(t)$$
$$= \underbrace{a}\, e^{i\overbrace{\phi}}\, s(t - \underbrace{\tau}) + n(t)$$

Parameters

- **Sampled multivariate complex Gaussian PDF**

$$p(\underline{\mathbf{z}};\tau,a,\phi) = \frac{1}{(\pi\,\sigma_n^2)^{n_s}}\, e^{-\{(\underline{\mathbf{z}}-a\,e^{i\phi}\,\underline{\mathbf{s}}_\tau)\,(\underline{\mathbf{z}}-a\,e^{i\phi}\,\underline{\mathbf{s}}_\tau)^\dagger/\sigma_n^2\}}$$
$$= \frac{1}{(\pi\,\sigma_n^2)^{n_s}}\, e^{-\sum_m \|z(mT_s)-a\,e^{i\phi}\,s(mT_s-\tau)\|^2/\sigma_n^2}$$

- **Observe signal is in the mean**

$$\underline{\boldsymbol{\mu}} = a\,e^{i\phi}\,\underline{\mathbf{s}}(t-\tau)$$

- **Estimate delay by maximizing likelihood**

$$\hat{\tau} = \operatorname{argmax}_{\tau;a,\phi}\, p(\underline{\mathbf{z}};\tau,a,\phi)$$

# Delay Bound

- **Adjust parameter origins to zero off-diagonal elements**
  - **Just need to worry about delay term**

$$\underbrace{\mathbf{J}}_{\text{Fisher Information Matrix}} = \begin{pmatrix} J_{\tau,\tau} & 0 & 0 \\ 0 & J_{a,a} & 0 \\ 0 & 0 & J_{\phi,\phi} \end{pmatrix}$$

**Fisher Information Matrix**

- **Go back to standard definition**

$$J_{\tau,\tau} = \left\langle \left( \frac{\partial}{\partial \tau} \log p(z;\tau,a,\phi) \right) \left( \frac{\partial}{\partial \tau} \log p(z;\tau,a,\phi) \right)^{*} \right\rangle$$

- **Derivative with respect to delay**

$$\begin{aligned} \frac{\partial}{\partial \tau} \log p &= -\sum_m [n^*(m\,T_s)\,a\,e^{i\phi}\,\frac{\partial}{\partial \tau} s(m\,T_s - \tau) + n(m\,T_s)\,a\,e^{-i\phi}\,\frac{\partial}{\partial \tau} s^*(m\,T_s - \tau)] \\ &= -\sum_m [n^*(m\,T_s)\,a\,e^{i\phi}\,\frac{\partial}{\partial \tau} s(m\,T_s - \tau) + c.c.] \end{aligned}$$

# Evaluate Delay CRB

- **Basic derivation**

$$J_{\tau,\tau} = \left\langle \left( \frac{\partial \log p(\underline{\mathbf{z}}_\tau)}{\partial \tau} \right)^2 \right\rangle$$

$$= \left\langle \left\| \sum_m [n^*(m T_s)\, a\, e^{i\phi} \frac{\partial}{\partial \tau} s(m T_s - \tau) + c.c. \right\|^2 \right\rangle$$

$$= 2 \sum_m \left\langle n^*(mT_s)\, a\, e^{i\,\phi} \frac{\partial}{\partial \tau} s(m T_s - \tau)\, [n(mT_s)\, a\, e^{-i\,\phi} \frac{\partial}{\partial \tau} s^*(m T_s - \tau)] \right\rangle$$

$$= 2\, a^2 \sum_m \left\langle \frac{\partial}{\partial \tau} s(m T_s - \tau)\, \frac{\partial}{\partial \tau} s^*(m T_s - \tau) \right\rangle$$

- **Leverage Parseval**

$$\left\langle \left\| \frac{\partial}{\partial \tau} s(m T_s - \tau) \right\|^2 \right\rangle = \langle \| -2\pi\, f\, i\, S(-f)\, e^{-i\, 2\pi m\, T_s} \|^2 \rangle$$

$$= (2\pi)^2\, \langle \| f\, S(f) \|^2 \rangle$$

$$= (2\pi)^2\, B_{\text{rms}}^2\, \langle \| S(f) \|^2 \rangle$$

$$= (2\pi)^2\, B_{\text{rms}}^2\, \langle \| s(m\, T_s - \tau) \|^2 \rangle = (2\pi)^2\, B_{\text{rms}}^2$$

$$B_{\text{rms}}^2 = \frac{\langle \| f\, S(f) \|^2 \rangle}{\langle \| S(f) \|^2 \rangle}$$

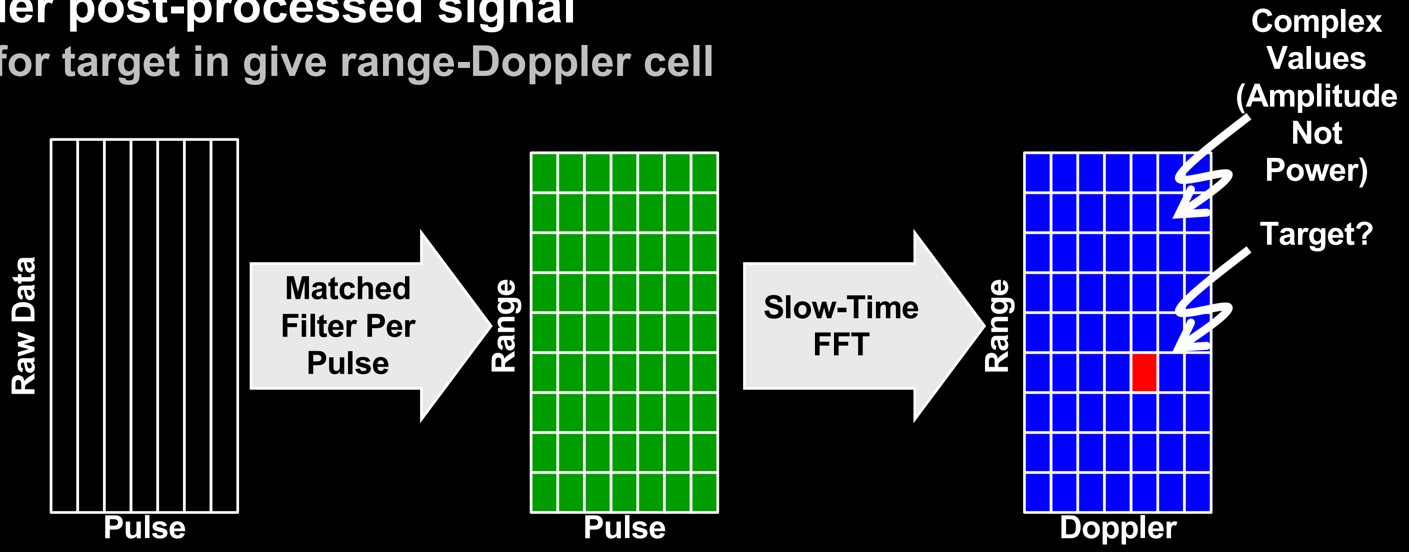
$$\langle f\, \| S(f) \|^2 \rangle = 0$$

$$\frac{1}{J_{\tau,\tau}} = \frac{1}{2\, a^2} \frac{1}{(2\pi)^2\, B_{\text{rms}}^2}$$

$$= \frac{1}{8\pi^2\, B_{\text{rms}}^2} \frac{1}{\text{ISNR}}$$

# Neyman-Pearson Analysis for Nonfluctuating Target Under Range-Doppler Processing

- Consider deterministic, nonfluctuating target
- Consider post-processed signal
  - Test for target in give range-Doppler cell




- Find likelihood ratio test (NP)
- Evaluate ROC

# Nonfluctuating Target

## *Probability Densities*

- **Neyman-Pearson**
  - Use log likelihood ratio

$$L = \log_e \left[ \frac{p(z|H_1)}{p(z|H_0)} \right]$$

- **Noise, $H_0$**

$$p(z) = \frac{1}{\pi\, \sigma_n^2} e^{-\|z\|^2/\sigma_n^2}$$

- **Noise plus deterministic target, $H_1$**
  - Ricean (sort of square root of noncentral Chi square with 2 degrees)

$$p(z) = \frac{1}{\pi\, \sigma_n^2} e^{-(\|z\|^2+\mu^2)/\sigma_n^2}\ I_0\left( \frac{2\mu\|z\|}{\sigma_n^2} \right)$$

Target Mean
At Output of Processing

Modified Bessel Function
Of First Kind

# Nonfluctuating Target

## *Neyman-Pearson*

- **Compare likelihoods**
  - Use log likelihood ratio

$$L = \log_e \left[ \frac{p(z|H_1)}{p(z|H_0)} \right] \lessgtr \log_e(\eta)$$

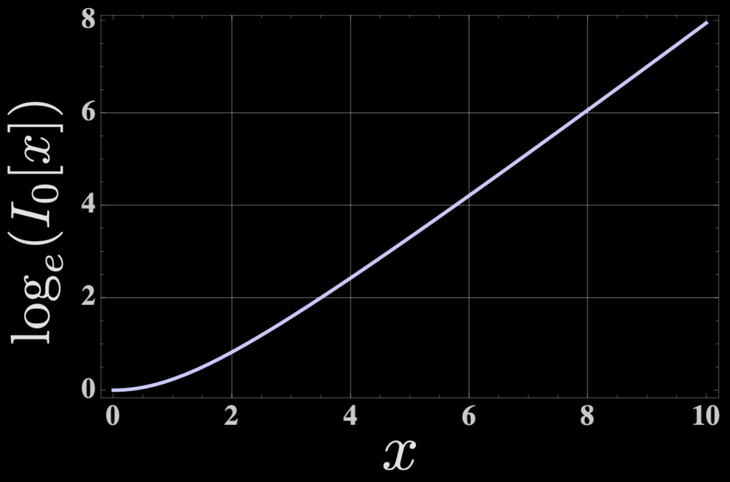
$$= \log_e \left[ \frac{\frac{1}{\pi\,\sigma_n^2}\, e^{-(\|z\|^2+\mu^2)/\sigma_n^2}\; I_0\!\left(\frac{2\mu\|z\|}{\sigma_n^2}\right)}{\frac{1}{\pi\,\sigma_n^2}\, e^{-\|z\|^2/\sigma_n^2}} \right] \lessgtr \log_e(\eta)$$

$$= \log_e \left[ e^{-(\mu^2)/\sigma_n^2}\; I_0\!\left(\frac{2\mu\|z\|}{\sigma_n^2}\right) \right] \lessgtr \log_e(\eta)$$

$$= \log_e \left[ I_0\!\left(\frac{2\mu\|z\|}{\sigma_n^2}\right) \right] - \mu^2/\sigma_n^2 \lessgtr \log_e(\eta)$$

$$= \log_e \left[ I_0\!\left(\frac{2\mu\|z\|}{\sigma_n^2}\right) \right] \lessgtr \log_e(\eta) + \mu^2/\sigma_n^2 = \eta'$$

- **Monotonic, really just use** $\|z\| \lessgtr \eta''$



# Nonfluctuating Target

## *Magical Knowledge Performance,* $P_{\mathrm{FA}} - P_{\mathrm{D}}$

- **Test signal within a range-Doppler bin**
  - Variable that we care about $x = \|z\|\,, \quad \text{or} \quad q = \|z\|^2$

- **$H_0$, Noise**
  - Rayleigh,

$$p(x|H_0) = \frac{2x}{\sigma_n^2}\, e^{-x^2/\sigma_n^2}$$

$$P_{\mathrm{FA}} = \int_\eta^\infty dx\, p(x|H_0)$$

$$= \int_\eta^\infty dx\, \frac{2x}{\sigma_n^2}\, e^{-x^2/\sigma_n^2}$$

$$= e^{-\eta^2/\sigma_n^2}$$

$$\eta = \sigma_n \sqrt{-\log_e(P_{\mathrm{FA}})}$$

Closed-Form Threshold

- **$H_1$, Nonfluctuating signal plus noise**
  - Could use noncentral Chi square
  - Ricean,

$$p(x|H_1) = \frac{2x}{\sigma_n^2}\, e^{-(x^2+\mu^2)/\sigma_n^2}\; I_0\!\left(\frac{2\,\mu^2\,x}{\sigma_n^2}\right)$$

$$P_{\mathrm{D}} = \int_\eta^\infty dx\, p(x|H_1)$$

$$= \int_\eta^\infty dx\, \frac{2x}{\sigma_n^2}\, e^{-(x^2+\mu^2)/\sigma_n^2}\; I_0\!\left(\frac{2\,\mu^2\,x}{\sigma_n^2}\right)$$

$$= Q_M\!\left(\sqrt{\frac{2\,\mu^2}{\sigma_n^2}}, \sqrt{\frac{2\,\eta^2}{\sigma_n^2}}\right)$$

$$Q_M(\alpha, T) = \int_T^\infty dt\, t\, e^{-(t^2+\alpha^2)/2}\, I_0(\alpha\, t)$$

Marcum Q-Function

# Nonfluctuating Target

## *Magical Knowledge Performance,* $P_\text{D}$-$P_\text{FA}$

- **Evaluate receiver operating characteristics (ROC) curve False alarm**
  - **Probability of false alarm**

$$P_\text{FA} = e^{-\eta^2/\sigma_n^2}$$

$$\eta = \sigma_n \sqrt{-\log_e(P_\text{FA})}$$

  - **Probability of detection**

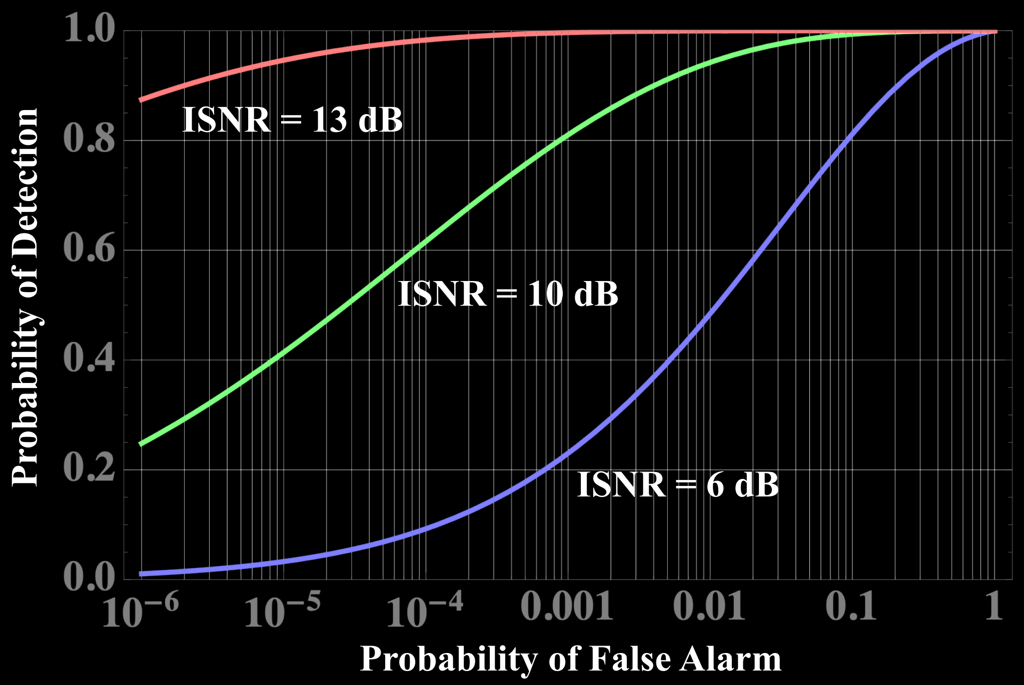
$$P_\text{D} = Q_M\left(\sqrt{\frac{2\,\mu^2}{\sigma_n^2}}, \sqrt{\frac{2\,\eta^2}{\sigma_n^2}}\right)$$

    - $Q_M$ is Marcum Q-function

- **Put it all together**

$$P_\text{D} = Q_M\left(\sqrt{2\,\text{ISNR}}, \sqrt{-2\,\log_e(P_\text{FA})}\right)$$

$$\text{ISNR} = \frac{\mu^2}{\sigma_n^2}$$

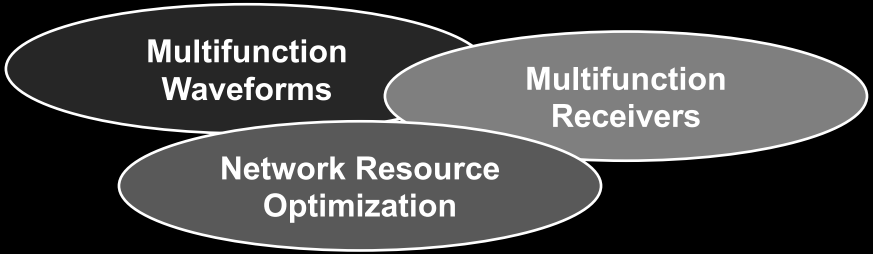


# How Do We Get There?

- Review Goals and Implications of Heilmeier Questions
- Underlying Physics of Applications
- Explore New Enabling Technologies
- Explore Metrics of Performance
- **Investigate Examples**

# Spectral Convergence

- **Reuse RF/mmWave signals and receivers**
  - Node performs multiple tasks simultaneously with same energy
  - Remove artificial separation between communications, sensing, PNT, etc.

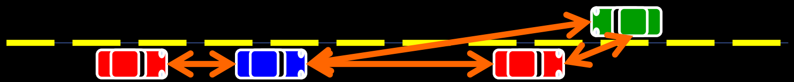



- **Improve rather than degrade performance by friendly RF/mmWave systems**
  - Radios can do everything
- **Enabled by recent technical advances**
  - Efficient flexible computational systems
  - Flexible RF

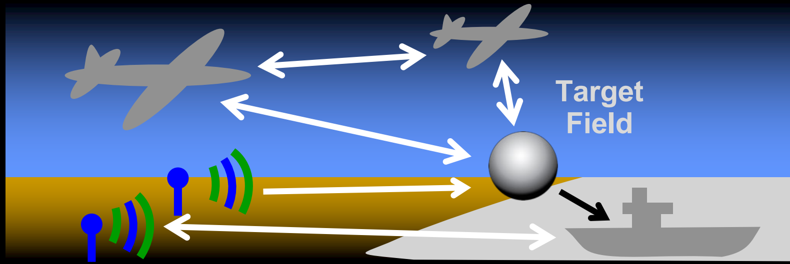
Potential Convergence Examples

mmWave Comms & Gesture Recognition Radar


Automotive



Military Systems

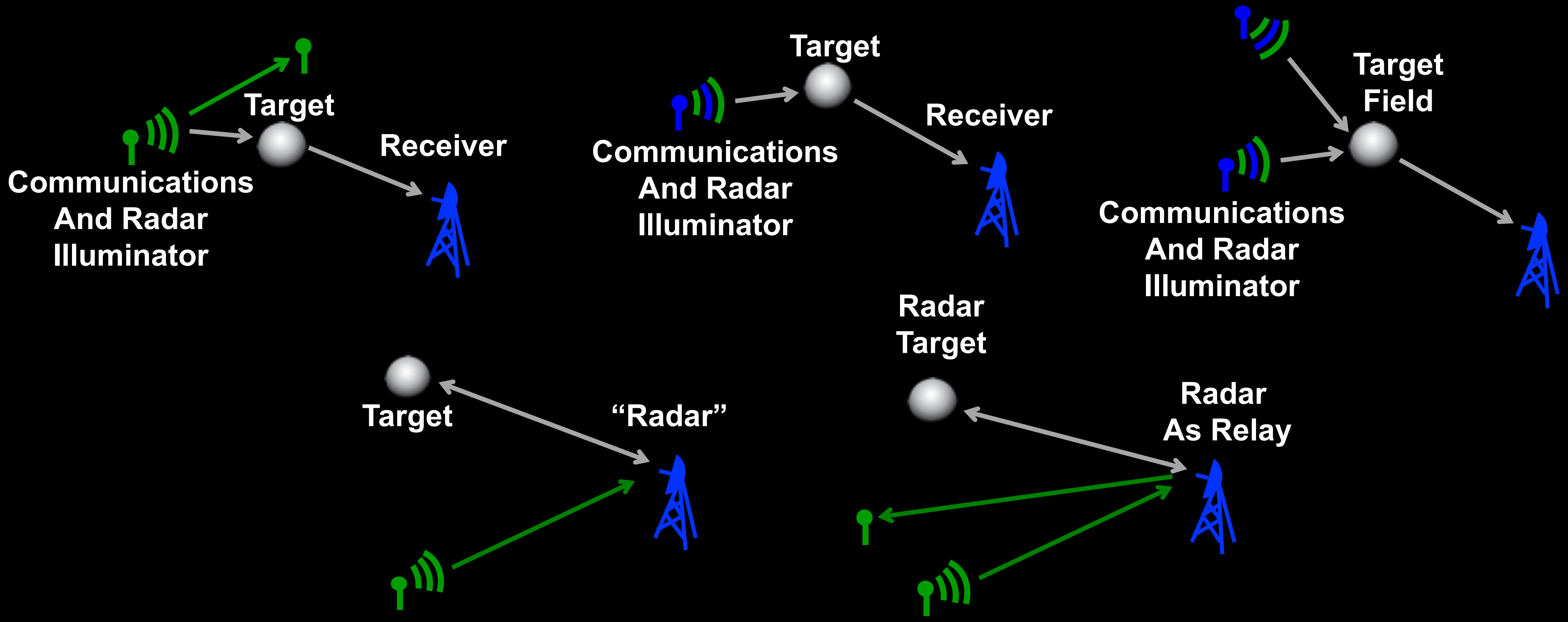



B. Paul, A. R. Chiriyath, and D. W. Bliss "Survey of RF Communications and Sensing Convergence Research," IEEE Access, Dec., 2016.

# Simple Topological Models

*Communications and Radar Examples*

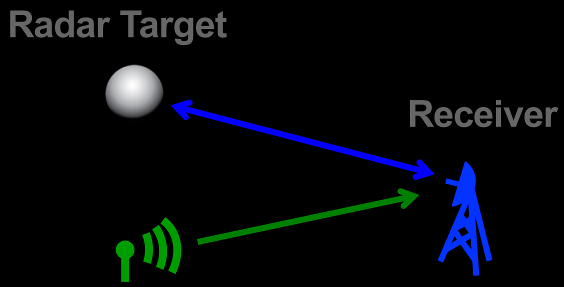
**Decompose more complicated networks into basic components**

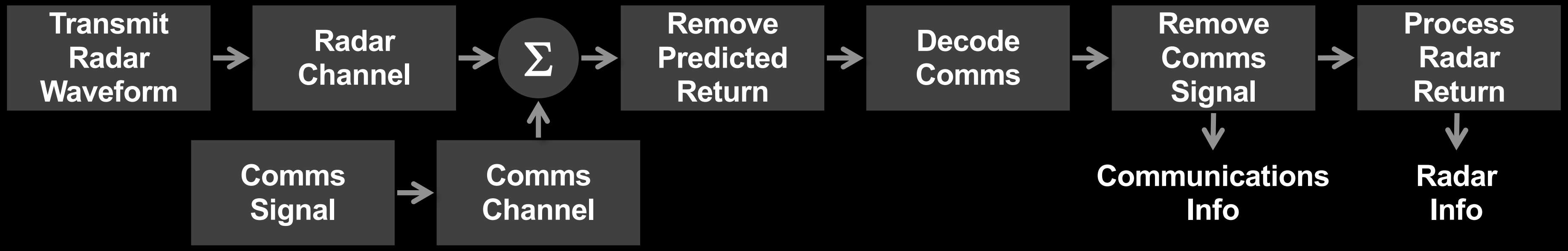


# Multi-Access Communications & Radar

## *Example Approach*

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



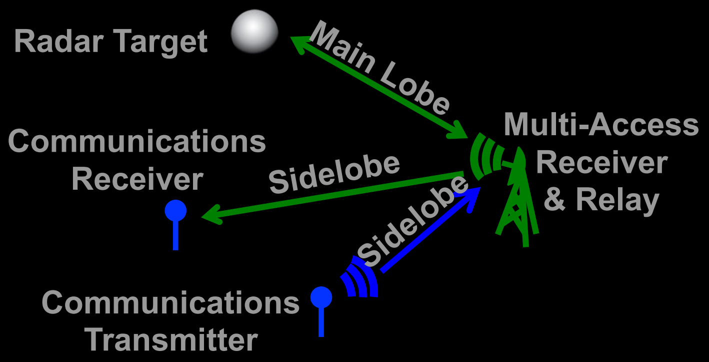




D. W. Bliss, "Cooperative radar and communications signaling: The estimation and information theory odd couple," *IEEE Radar Conference*, 2014

# Multi-Access Receive and Relay

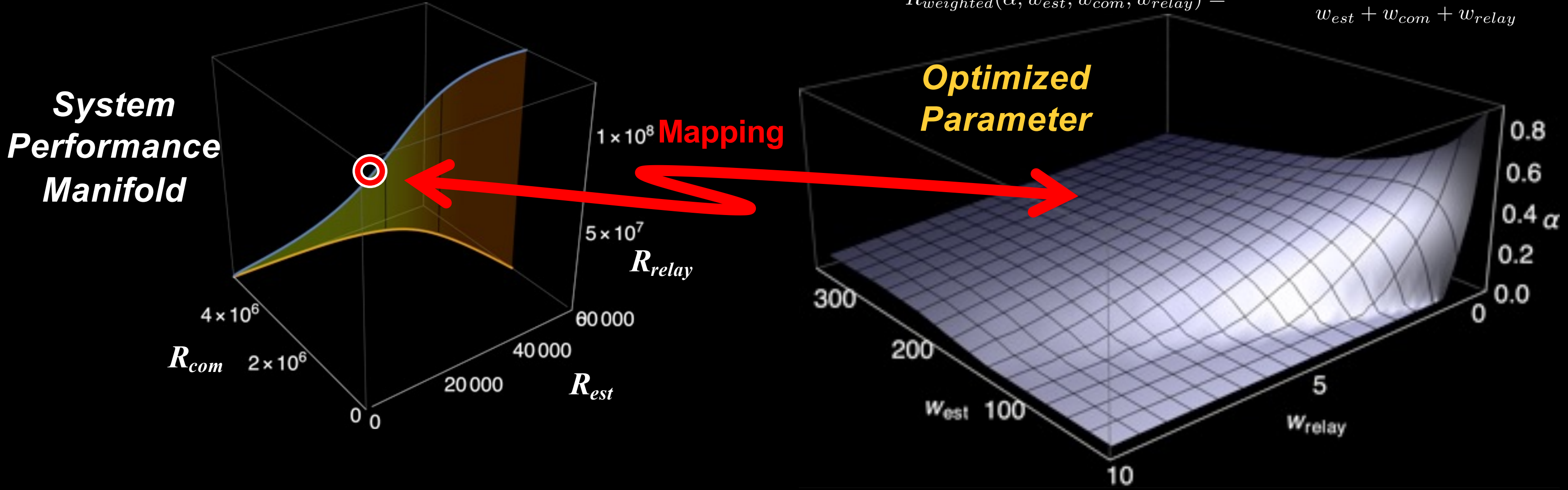
## *Simple Example*

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




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

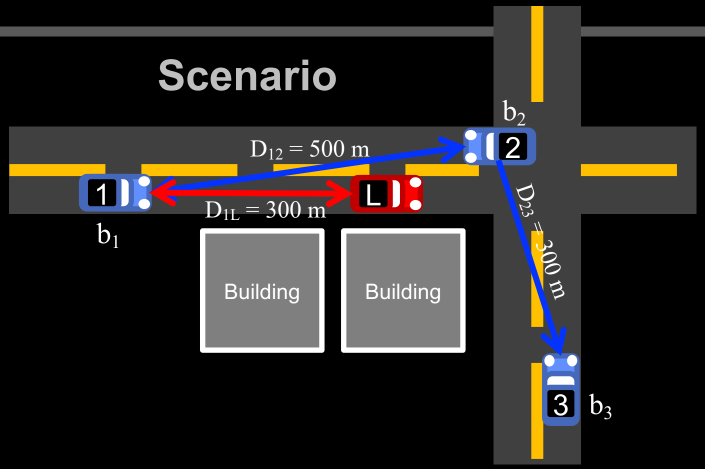
$$R_{weighted}(\alpha; w_{est}, w_{com}, w_{relay}) = \frac{w_{est}\,R_{est} + w_{com}\,R_{com} + w_{relay}\,R_{relay}}{w_{est} + w_{com} + w_{relay}}$$



# Toy Automotive Problem

- Consider joint communications; radar; and positioning, navigation, and timing (PNT) problem
- Communicate to Car 3 that legacy (L) vehicle is approaching intersection
- Use waveforms for comms, radar, and PNT
- Trade bandwidth between users

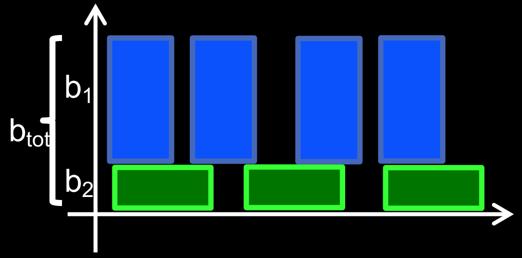
## Scenario



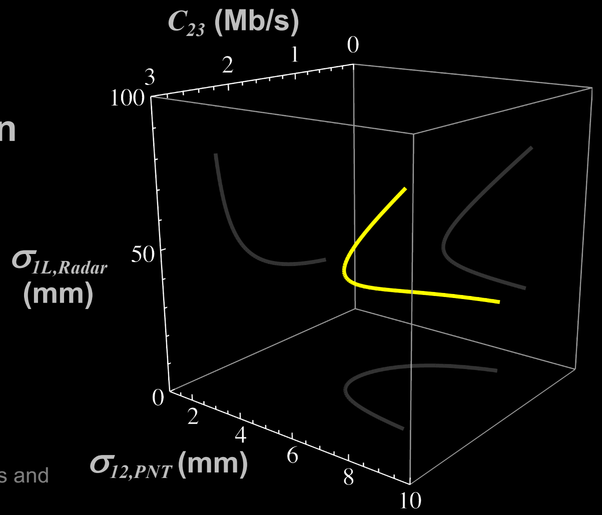

### Parameters

- Center frequency = 77 GHz
- Total bandwidth (1&2) = 1 GHz,
- Transmit power = 1W
- Noise figure = 6 dB, T = 300K
- Coding loss = -6 dB
- Chirp TBP = 30 dB, Slow-time TBP = 20 dB
- PNT TBP = 100 chirps
- RCS = 10 $m^2$
- Antenna gain
  - 13dB (forward)
  - (1 ↔ 2) = 0 dB, (2 → 3) = -6 dB, (3 → 2) = 0 dB,

## Chirp Pulse Position Modulation




## Performance Manifold




A. Herschfelt, A. R. Chiriyath, S. Srinivas, D. W. Bliss, “An Introduction to Spectral Convergence: Challenges and Paths to Solutions,” IEEE International Online Symposium on Joint Communications & Sensing, 2021

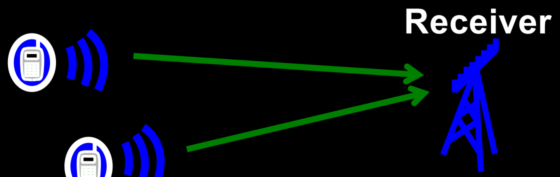
# Multiple Access Communications Bound

## *Illustrative Analogy*

- **Satisfy all bound**

$$R_1 \leq \log_2(1 + a_1^2 P_1)$$
$$R_2 \leq \log_2(1 + a_2^2 P_2)$$
$$R_1 + R_2 \leq \log_2(1 + a_1^2 P_1 + a_2^2 P_2)$$

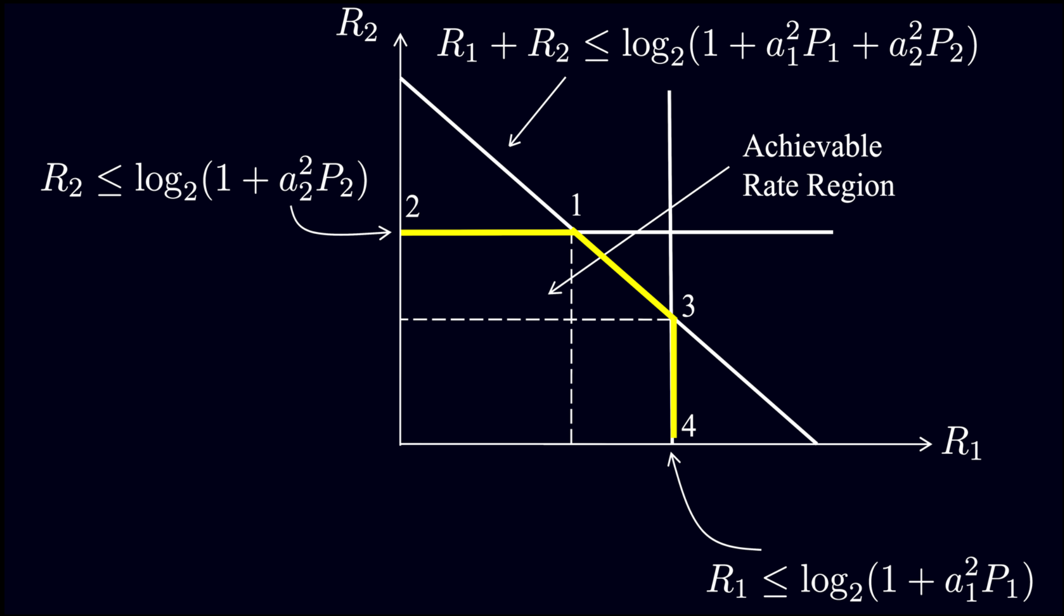
  - **Fix power of channel for both transmitters**




- **Find points of bound intersection**

$$R_2 = \log_2(1 + a_2^2 P_2)$$
$$R_1 + R_2 - R_2 = \log_2(1 + a_1^2 P_1 + a_2^2 P_2) - \log_2(1 + a_2^2 P_2)$$
$$R_1 = \log_2\left(\frac{1 + a_1^2 P_1 + a_2^2 P_2}{1 + a_2^2 P_2}\right)$$
$$\{R_1,\, R_2\} = \left\{\log_2\left(1 + \frac{a_1^2 P_1}{1 + a_2^2 P_2}\right),\, \log_2(1 + a_2^2 P_2)\right\}$$
$$\{R_1,\, R_2\} = \left\{\log_2(1 + a_1^2 P_1), \log_2\left(1 + \frac{a_2^2 P_2}{1 + a_1^2 P_1}\right)\right\}$$

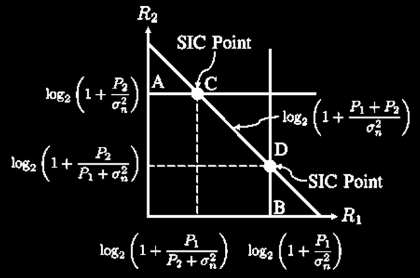
**Multiple Access Bound**

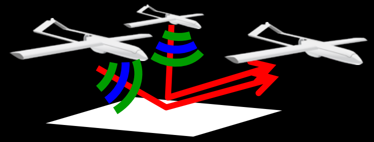


# Multiuser Communications & Multi-Static SAR

## *MATLAB Simulation*

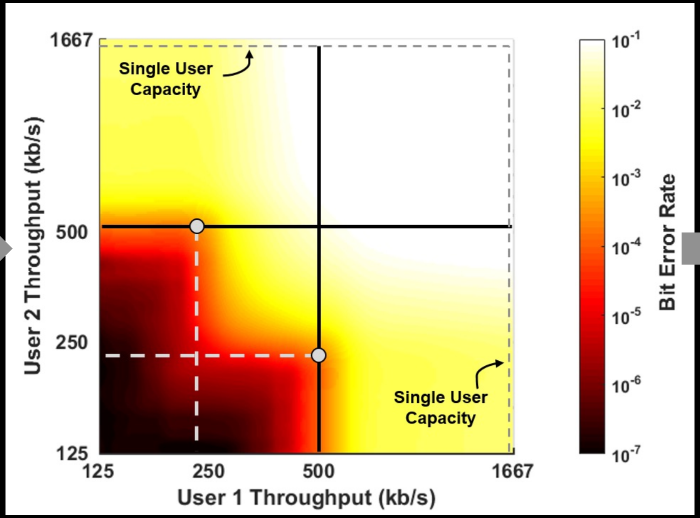
- **Design joint radar-communications system**
- **Develop multi-static channel model**
- **Approach performance bounds**
- **Perform SAR imaging**



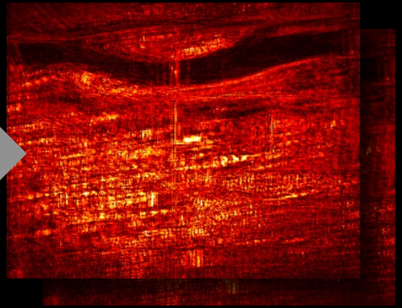



**Modeled Scattering Field**

**Successive Interference Cancellation**




**Multi-Static Synthetic Aperture Radar Image**

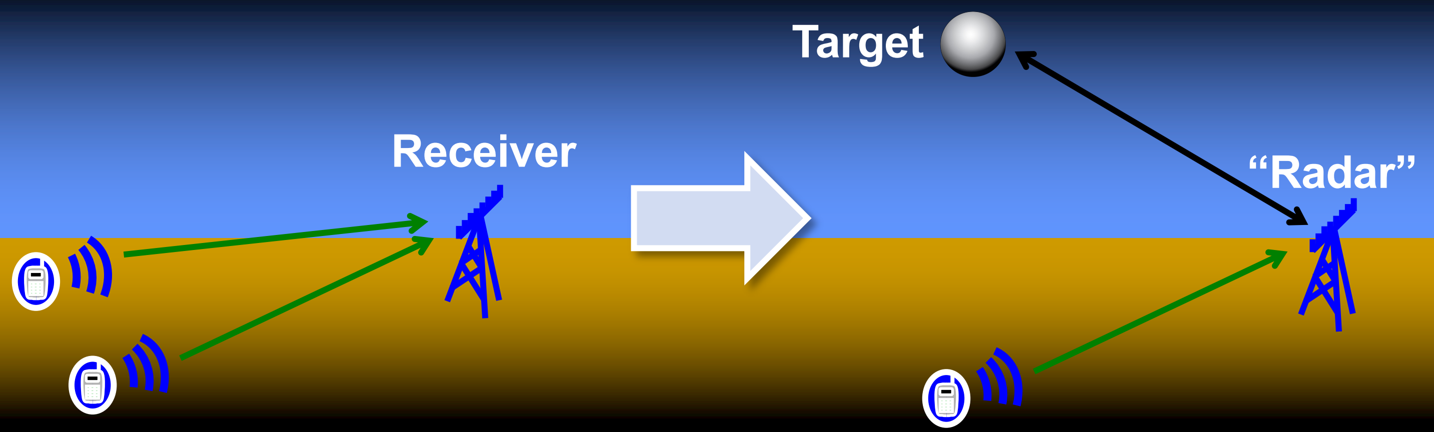


A. Herschfelt and D. W. Bliss, "Joint radar-communications waveform multiple access and synthetic aperture radar receiver," *IEEE Asilomar Conference on Signals, Systems, and Computers*, Pacific 2017

# Multiple Access Radar/Comms Receiver

## *Are The Bounds Equivalent?*

- **Equivalent? No**
  - Estimation is not drawn from countable distribution
  - Bound is not achievable




- **But, let's see how close we can get**
  - Focus on achievable (inner) bounds

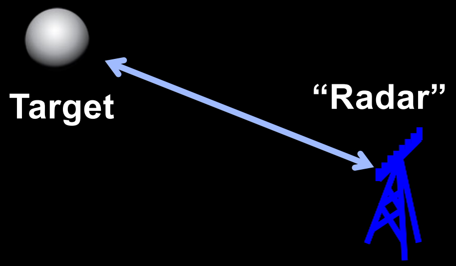
***Hint:***
**We Will Apply MUD to Mixed Radar and Communications**

D. Bliss, "Cooperative Radar and Communications Signaling: The Estimation and Information Theory Odd Couple," *in IEEE Radar Conference*, May 2014.

# Characterize What You Have Learned about the Target

## *Random Process Characterization*

- **Develop concept of estimation information rate**
  - Average bit rate required to encode knowledge of target




- **Estimate target range (delay)**

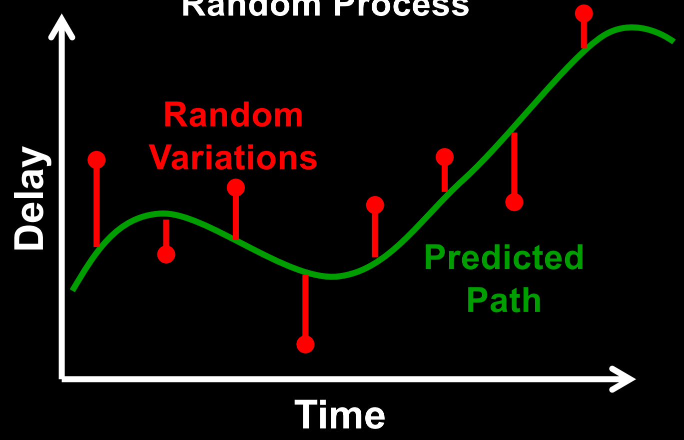
- **Assume delay determined by partially known random process**
  - Assume unknown delay is Gaussian

Target Delay

$$\tau_m^{(k)} = \tau_{m,\mathrm{pre}}^{(k)} + n_{\tau,\mathrm{proc}}$$

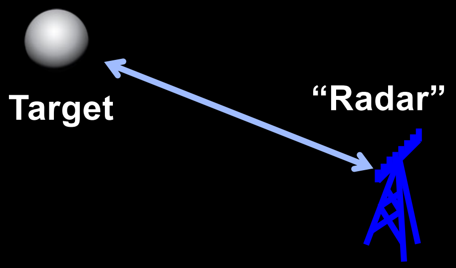
Target Delay Variance

$$\sigma^2_{\mathrm{proc}} = \langle n^2_{\tau,\mathrm{proc}} \rangle$$



# Range (Delay) Estimation Uncertainty

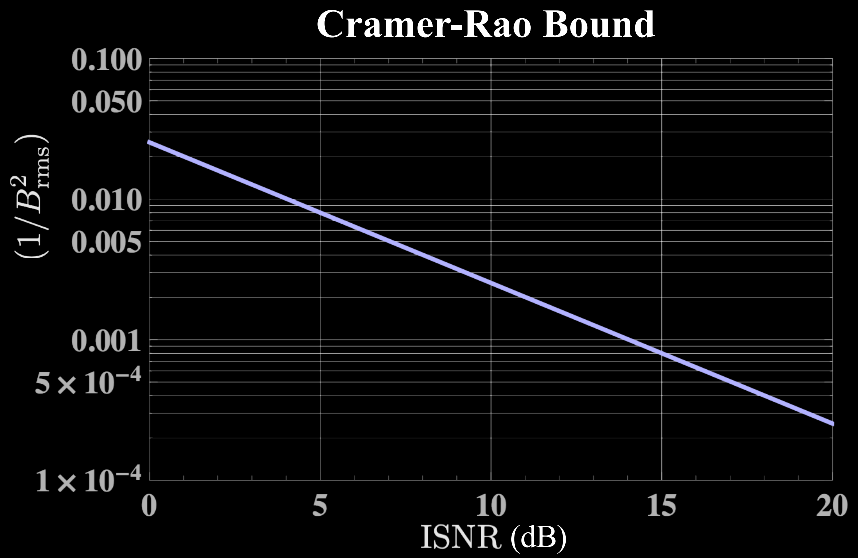
- **Assume good estimator and reasonable integrated SNR**
- **Use Cramer-Rao bound to get delay estimation performance bound**




$$\sigma^2_{\tau;\mathrm{est}} = \left( \frac{1}{8\pi^2 \, B^2_{\mathrm{rms}} \, \mathrm{ISNR}} \right)$$

$$B^2_{\mathrm{rms}} = \frac{\int \mathrm{d}f \, f^2 \, \|X(f)\|^2}{\int \mathrm{d}f \, \|X(f)\|^2}$$

$$\langle f \rangle = 0$$



# Target Information Rate

## *A Quirky Parameterization*

- **Invent target estimation rate**
  - **Assume process variation and estimation error are Gaussian**

- **Determine estimation information rate by evaluating total and estimation entropies**
  - $R_{\mathrm{est}} \sim H_{\mathrm{uncertainty}} - H_{\mathrm{est}}$
  - **Average number of bits required to encode estimate per unit time**

$$R_{\mathrm{est}} \leq \sum_m \frac{\delta}{2T} \log_2\left(1 + \frac{\sigma^2_{\tau_{\mathrm{m}},\mathrm{proc}}}{\sigma^2_{\tau_{\mathrm{m}},\mathrm{est}}}\right)$$

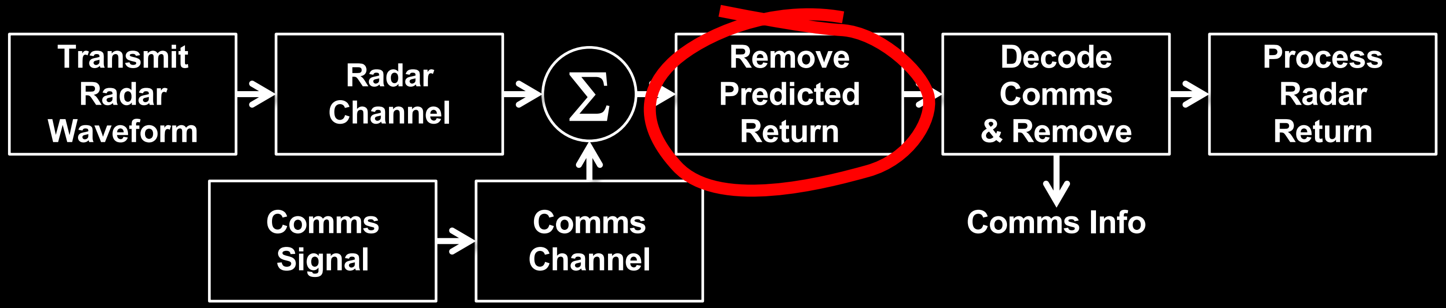
- **Ratio of variances looks like an “SNR”**
  - **Like SNR** $\frac{\sigma^2_{\tau,\mathrm{proc}}}{\sigma^2_{\tau,\mathrm{est}}}$

D. Bliss, “Cooperative Radar and Communications Signaling: The Estimation and Information Theory Odd Couple,” *IEEE Radar Conference*, May 2014.

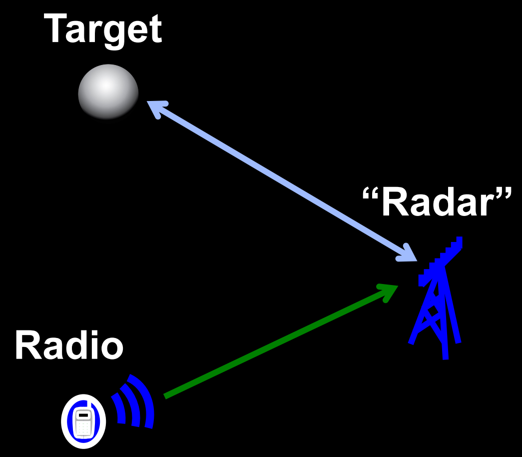
# Bound Approach Overview

## *Successive Interference Cancellation*

- **Construct novel joint radar/communications approach**



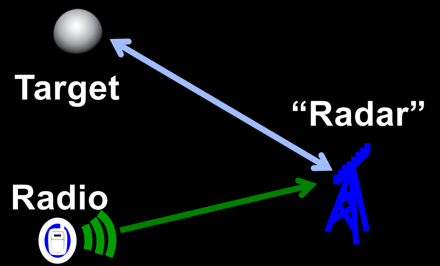

- **Basic successive interference cancellation (SIC) bound**
  - Define radar random process
  - Evaluate estimation error of radar
  - Evaluate estimation information rate
  - Evaluate communications capacity
  - Evaluate SIC point
  - Interpolate between SIC point and communications-only point



# Received Signal After Predicted Radar Return Removed

- **Received signal combines radar return and communications signal**

$$z(t) = \sqrt{P_{\text{com}}}\, b\, s_{\text{com}}(t) + \sqrt{P_{\text{radar}}} \sum_{m=1}^{N} a_m\, s_{\text{radar}}(t - \tau_m) + n(t)$$




- **Remove predicted radar return**

$$\tilde{z}(t) = \sqrt{P_{\text{com}}}\, b\, s_{\text{com}}(t) + n(t) + \sqrt{P_{\text{radar}}} \sum_{m=1}^{N} a_m [s_{\text{radar}}(t - \tau_m) - s_{\text{radar}}(t - \tau_{m,\text{pre}})]$$

- **Approximate difference with derivative**

$$\tilde{z}(t) \approx \sqrt{P_{\text{com}}}\, b\, s_{\text{com}}(t) + n(t) + \sqrt{P_{\text{radar}}} \sum_{m=1}^{N} a_m \frac{\partial s_{\text{radar}}(t - \tau_m)}{\partial t}\, n_{\tau,\text{proc}}$$

Not Required, But Provides Nice Result

- **Characterize "noise" to communications decoder at "radar"**

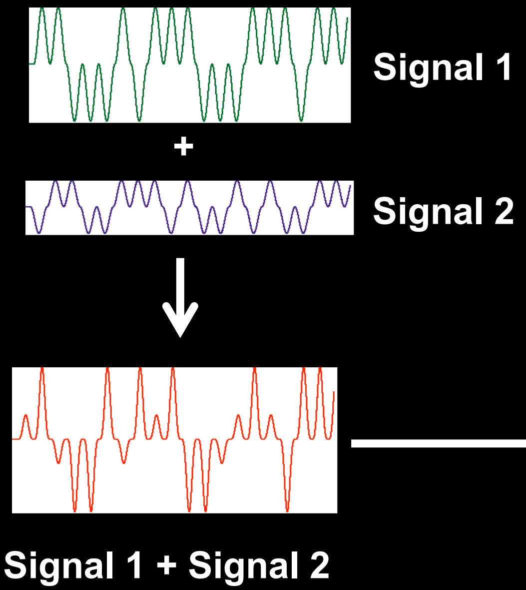
$$n_{\text{int+n}} = \sqrt{P_{\text{radar}}} \left( \sum_{m=1}^{N} a_m \frac{\partial s_{\text{radar}}(t - \tau_m)}{\partial t}\, n_{\tau,\text{proc}} \right) + n(t)$$

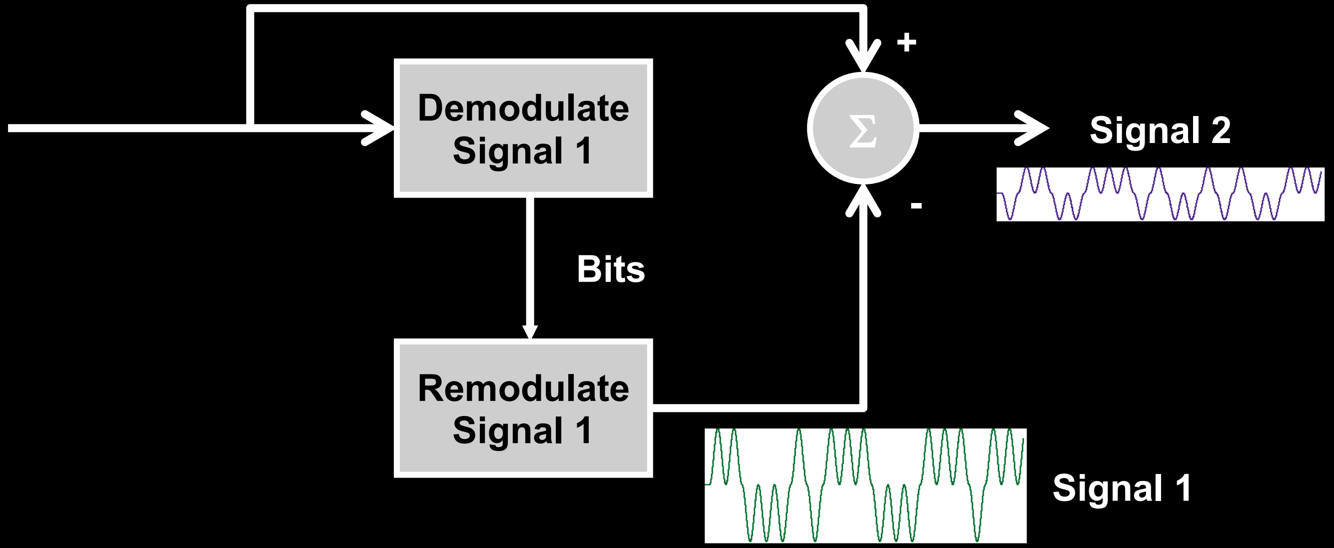
By Parseval's Theorem

$$\sigma^2_{\text{int+n}} = \langle \| n_{\text{int+n}} \|^2 \rangle$$

# Simple Successive Interference Cancellation (SIC)

- Decode stronger signal
- Remodulate stronger signal
- Subtract stronger signal
- Decode weaker signal



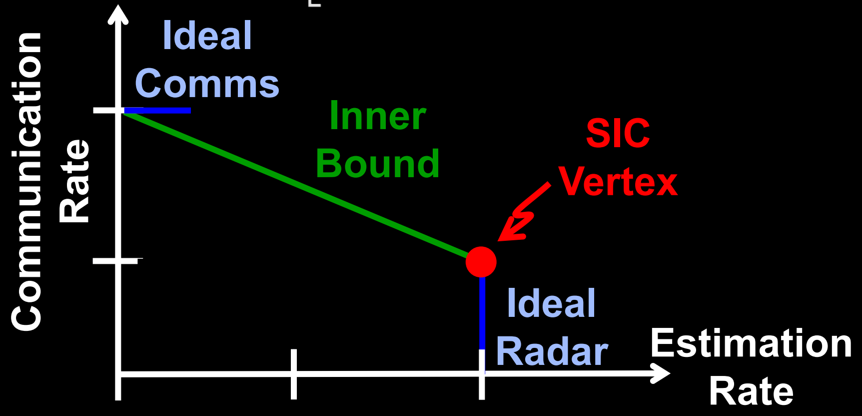
# Evaluate SIC Point

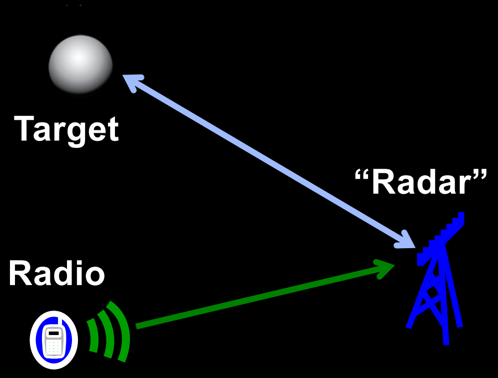
- **Find maximum communications rate such that the receiver can decode and subtract it in presence of radar return residual**

$$R_{\text{com}} \leq B\,\log_2\left[1 + \frac{b^2\,P_{com}}{\sigma^2_{\text{int+n}}}\right] = B\,\log_2\left[1 + \frac{b^2\,P_{com}}{\|a\|^2\,P_{\text{rad}}\,\gamma^2 B^2\,\sigma^2_{\text{proc}} + k_B\,T_{\text{temp}}\,B}\right]$$

- **Then have ideal radar range estimation**

$$R_{\text{est}} \leq \quad B\,\log_2\left[1 + \frac{2\sigma^2_{\tau,\text{proc}}\,\gamma^2\,B\,(TB)\,\|a_m\|^2\,P_{\text{rad}}}{k_B\,T_{\text{temp}}}\right]^{\delta/(TB)}$$

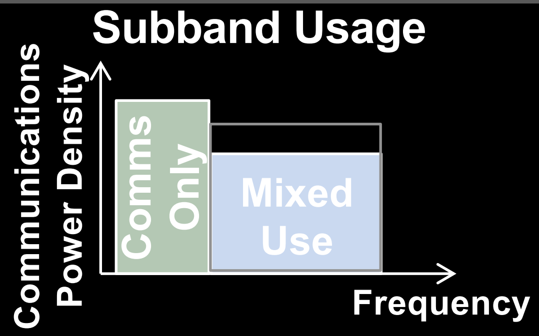


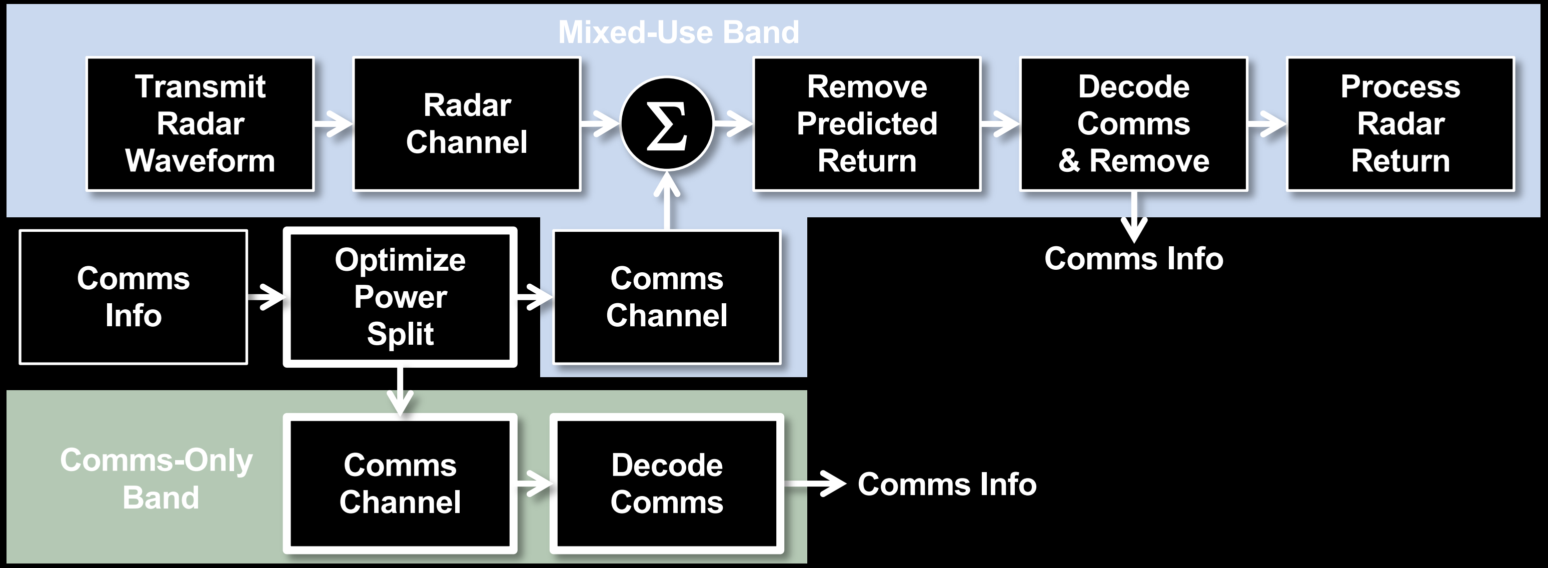



# Bound Approach Overview

## *Water-Filling Joint Waveform Design*

- **Split into two sub-bands**
  - Communications only
  - Mixed use
- **Optimize communications power use by employing water-filling**



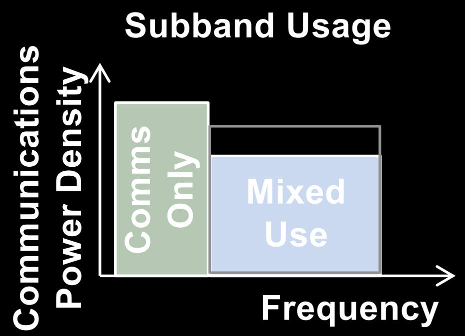

D. Bliss, "Cooperative Radar and Communications Signaling: The Estimation and Information Theory Odd Couple," *in IEEE Radar Conference*, May 2014.

# Distribute Power By "Water-Filling"

- **Optimize communications power/rate between bands**
  - Operate mixed-use band at SIC point

$$B = B_{\text{com}} + B_{\text{mix}}$$
$$B_{\text{com}} = \alpha\, B$$
$$B_{\text{mix}} = (1-\alpha)\, B$$

$$P_{\text{com}} = P_{\text{com,com}} + P_{\text{com,mix}}$$
$$P_{\text{com,com}} = \beta\, P_{\text{com}}$$
$$P_{\text{com,mix}} = (1-\beta)\, P_{\text{com}}$$




- **Define two channels**

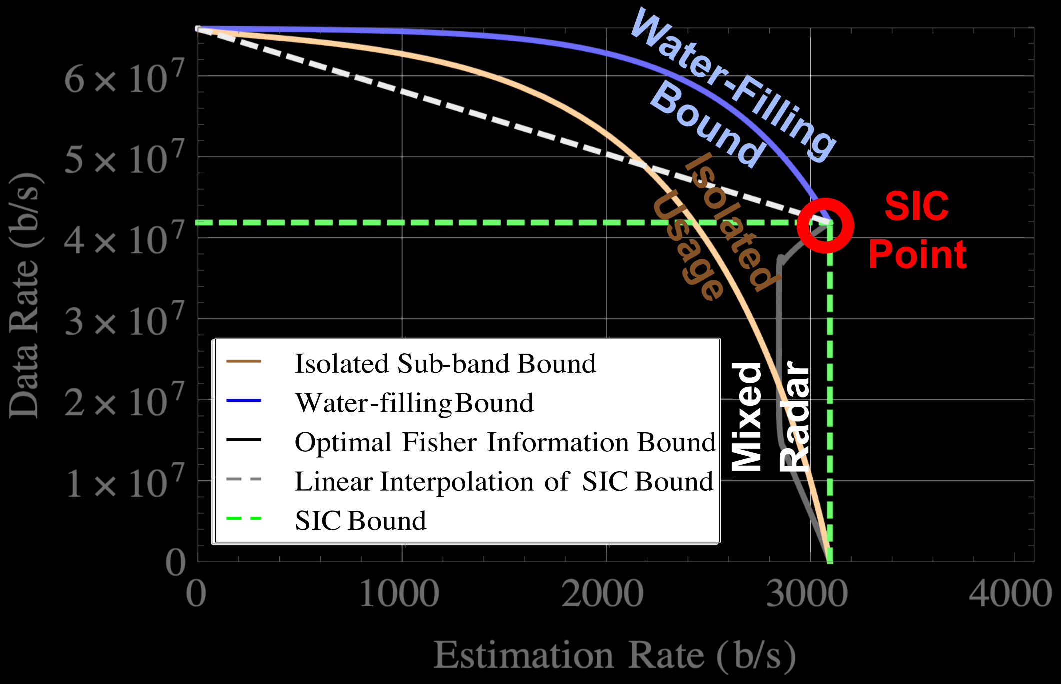
$$\mu_{\text{mix}} = \frac{b^2}{\sigma^2_{\text{int+n}}} \qquad \mu_{\text{com}} = \frac{b^2}{k_B\, T_{\text{temp}}\, B_{\text{com}}}$$

- **Optimal power distribution**

$$\beta = \frac{P_{\text{com,com}}}{P_{\text{com}}} = \alpha + \frac{1}{P_{\text{com}}}\left(\frac{\alpha-1}{\mu_{\text{com}}} + \frac{\alpha}{\mu_{\text{mix}}}\right) \text{ when } P_{\text{com}} \geq \frac{\alpha}{(1-\alpha)\,\mu_{\text{mix}}} - \frac{1}{\mu_{\text{com}}}$$

# Comparison of a Few Cooperative Operation Bounds

- **Compare inner bounds**
- **Bounded by water-filling approach currently**
  - Although its not tight



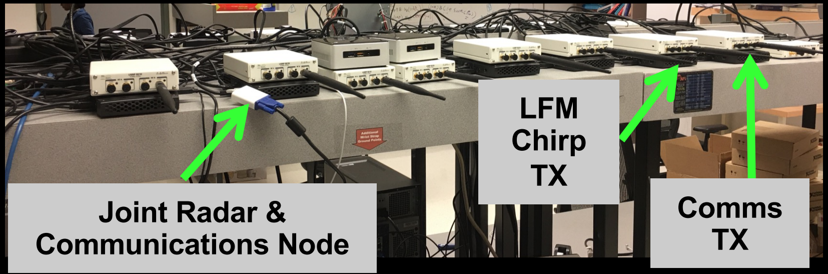

| Parameter | Value |
|---|---|
| Bandwidth | 5 MHz |
| Center Frequency | 3 GHz |
| Temperature | 1000 K |
| Communications Range | 10 km |
| Communications Power | 100 W |
| Communications Antenna Gain | 0 dBi |
| Communications Receiver Side-lobe Gain | 10 dBi |
| Radar Target Range | 100 km |
| Radar Antenna Gain | 30 dBi |
| Radar Power | 100 kW |
| Target Cross Section | 10 $m^2$ |
| Target Process Standard Deviation | 100 m |
| Time-Bandwidth Product | 100 |
| Radar Duty Factor | 0.01 |

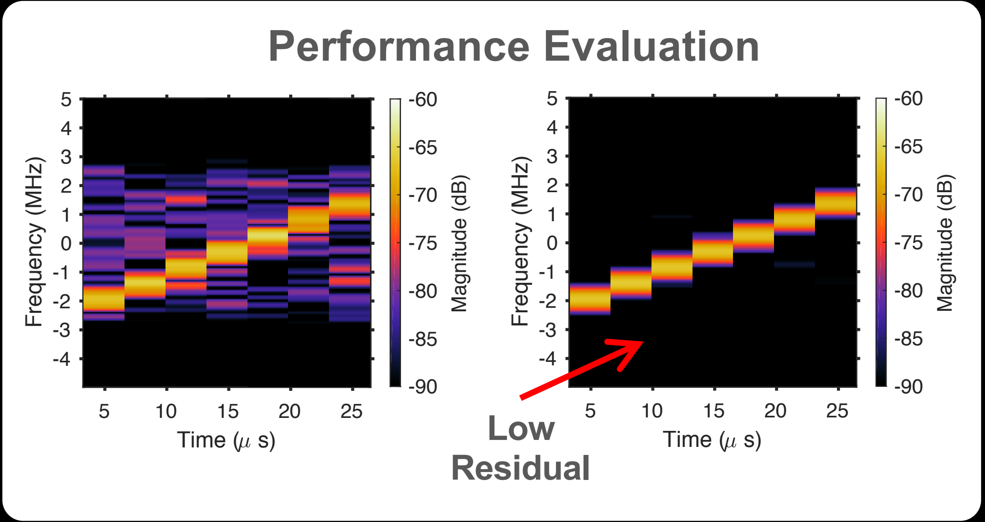
A. R. Chiriyath, B. Paul, G. M. Jacyna, and D. W. Bliss "Inner Bounds on Performance of Radar and Communications Co-Existence," *IEEE Transactions on Signal Processing*, Jan., 2016.

# 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**



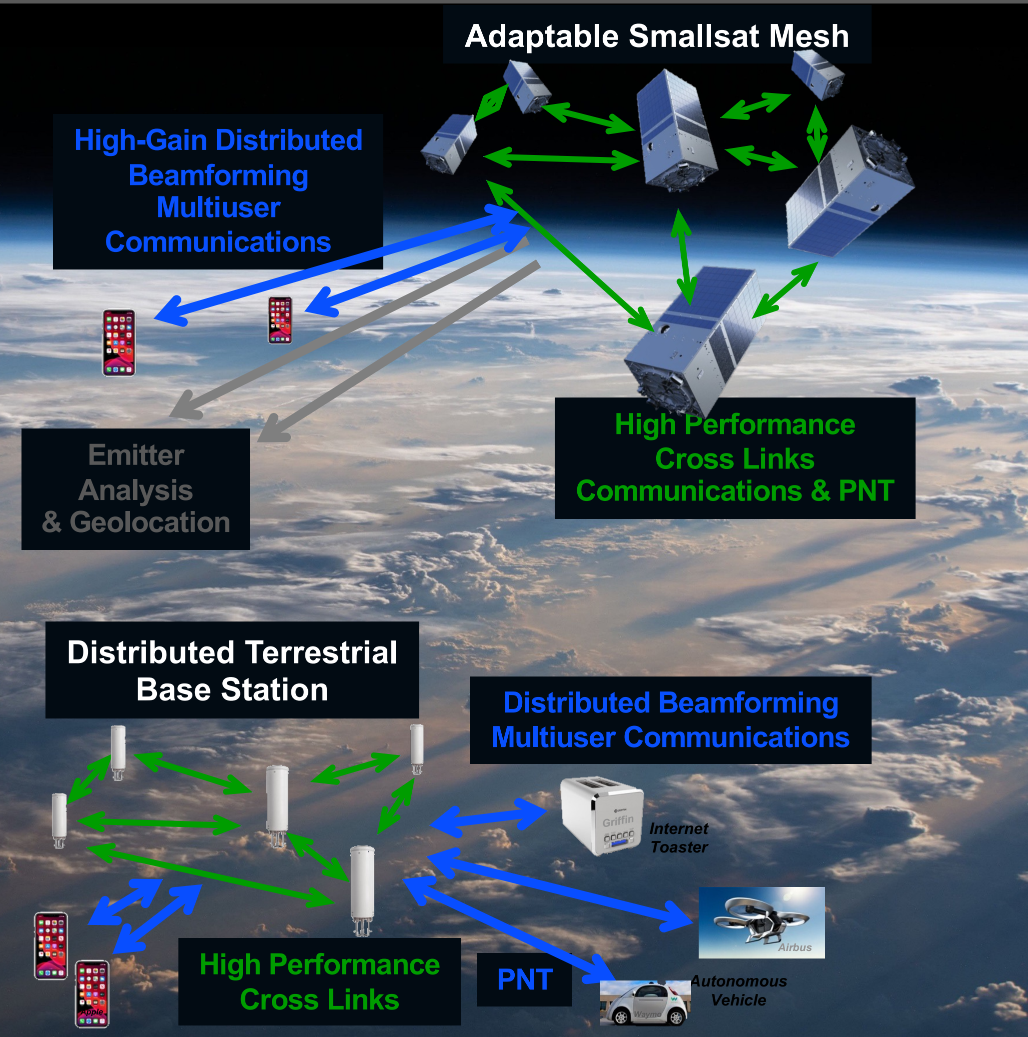




R. M. Gutierrez, A. Herschfelt, H. Yu, H. Lee and D. W. Bliss, "Joint radar-communications system implementation using software defined radios: Feasibility and results," IEEE Asilomar Conference on Signals, Systems, and Computers, 2017

# Advanced Reconfigurable Systems

*DC to Daylight*

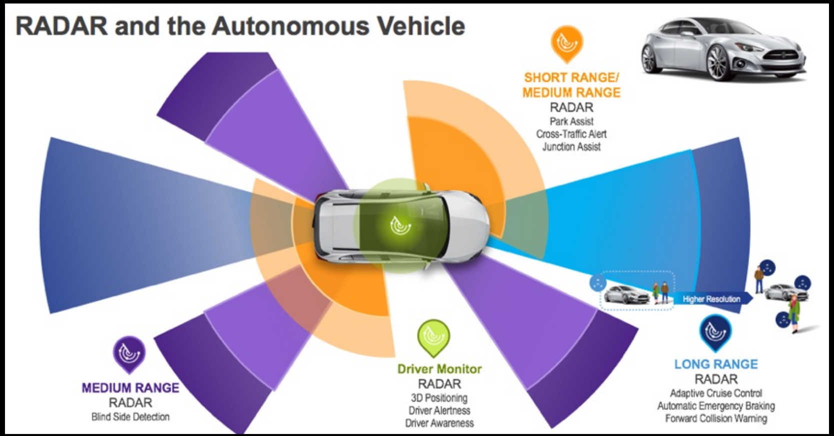
- **Reinvent spectral employment by co-design of multi-function system**
  - Provide transparent interface to spectrum
  - Higher data rate, better sensing, improved resilience
- **Enable RF convergence**
  - New functionalities
  - Multi-function systems
  - Communications, radar, PNT, etc…
- **Enable flexible distributed carrier phase-coherent systems**
  - Distributed wireless antenna arrays
- **Integrate proliferated low C-SWaP space**
- **Develop advanced flexible systems**
  - Bandwidth, power-scaling, dynamic range, …
  - Flexible RF and optical
  - Flexible computations



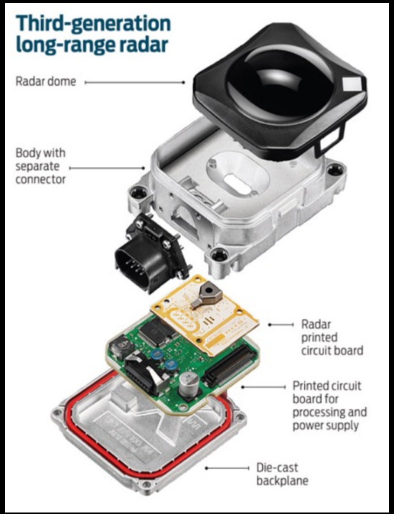
# Backup

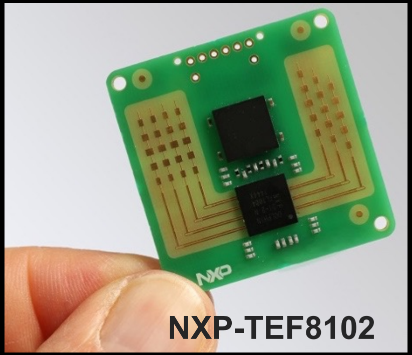
# Automotive Radars

- **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/



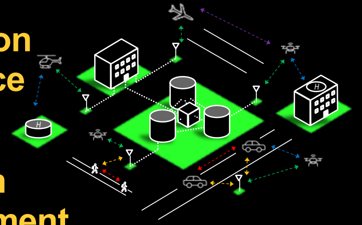

https://spectrum.ieee.org/transportation/advanced-cars/longdistance-car-radar

# WISCA Projects

## *Wireless Information Systems and Computational Architectures Center*

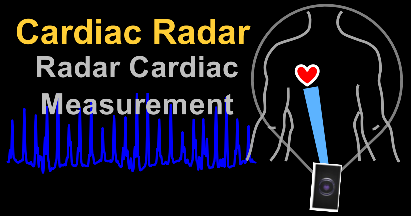
- Executing on a wide range of projects, large and small
- Developed strong relationships with industry and DoD sponsors

**Multiple-Function RF Convergence**

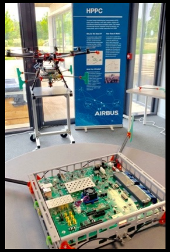


**Cardiac Radar**

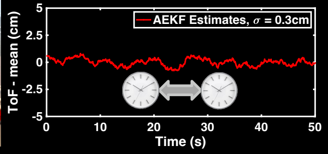
Radar Cardiac Measurement



**Advanced Positioning, Navigation, and Timing**

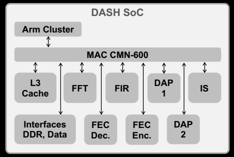


*Custom MIMO SDR, Novel Algorithms, Experimental Demo*

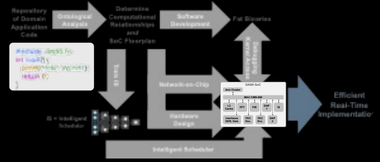



**Next Generation Processor Development**

*Heterogeneous Processors*




*Integrated Framework*

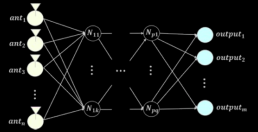


**Next Generation Signal Processing And Machine Learning**

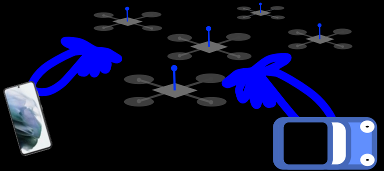
$$\mathbf{Z} \in \mathbb{C}^{(n_{ant} \cdot n_{tap}) \times n_{samp}}$$

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

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

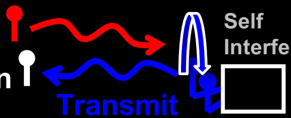


**Coherent Distributed Systems**



SPACEBACN

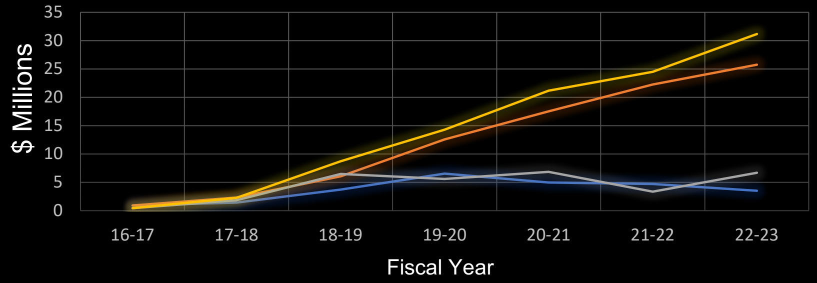

**In-Band Full Duplex**




**Recent Funding**

DARPA, L3HARRIS FAST. FORWARD., Google, NOKIA, Viasat, ONR, Raytheon, GENERAL DYNAMICS Mission Systems, NSF, str Systems & Technology Research, AIRBUS, AFOSR, LINCOLN LABORATORY Massachusetts Institute of Technology, Interstate Broadcasting, LLC, METAWAVE

**WISCA Awards and Expenditures**

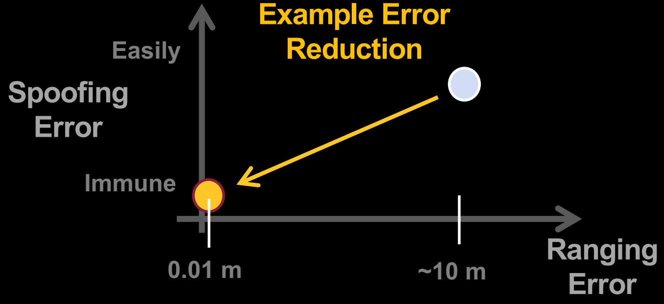


# Carrier Phase-Accurate Positioning, Navigation, and Timing

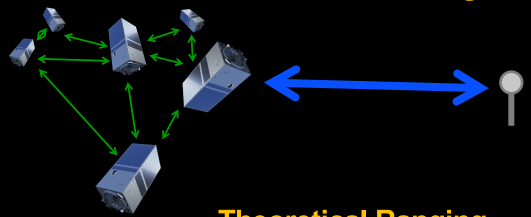
## *Enabling Distributed Beamforming Technology*

- **Enable distributed capabilities with distributed coherence**
  - Dramatically improve gain, P ~ $N^2$
  - Null interference and jamming
- **Exploit carrier phase-accurate timing exchange approaches for PNT**
  - Joint communications & PNT
  - Natural spoof resistance
- **Employ our advances in MIMO carrier phase-coherent timing exchanges**
  - Achieve 0.01m rather than 30m error

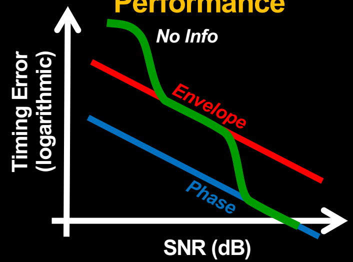
Example Error Reduction



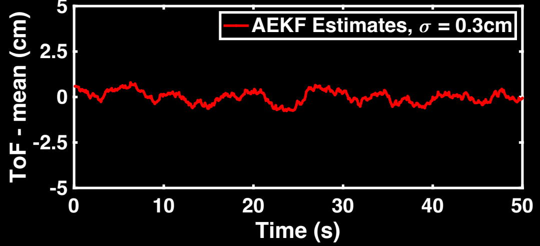

Distributed Beamforming



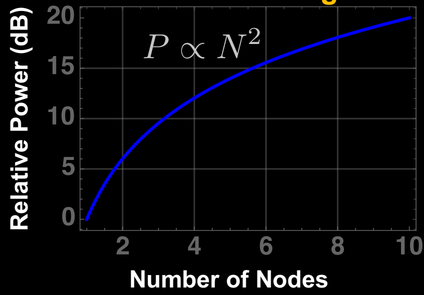
Theoretical Ranging Performance



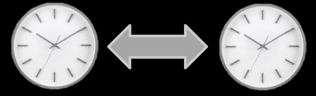

Experimental Ranging Results




Power Scaling




Distributed Coherence



ASU for Airbus System

# Backup