Cooperative Radar and Communications Signaling

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This work was sponsored in part by DARPA under the SSPARC program. The views expressed are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

Topics

- Why is this guy talking about radars?
- What do radars care about?
- What's the problem?
- How well can you do?
- Where do we go from here?

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Radars

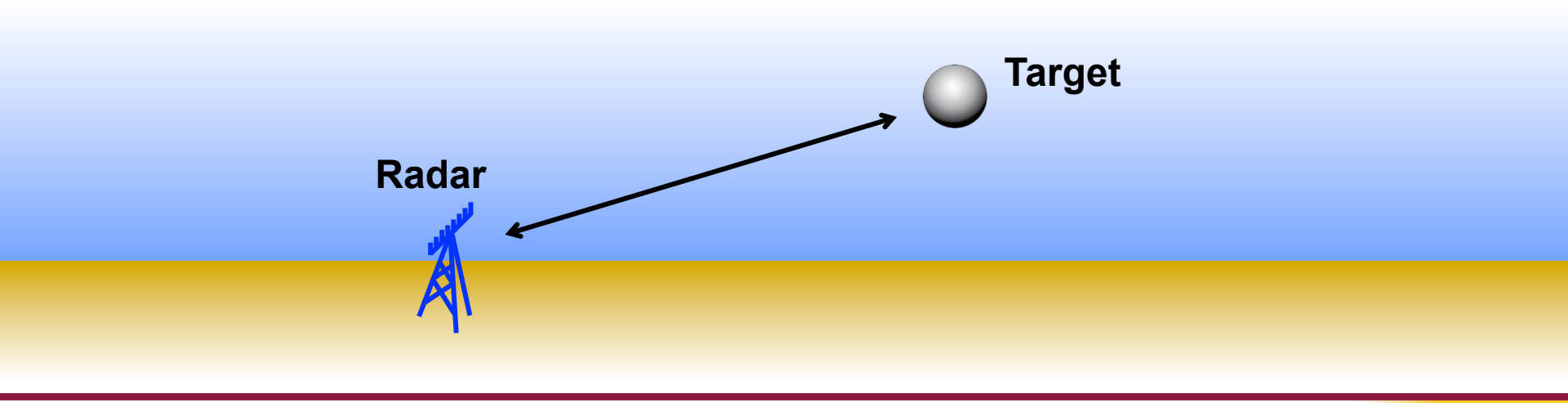
- That's that big dish thingy, right?

- Or, the thing the policed used to give me a ticket?

Although Laser Ranging is More Common Now

Simple Radar

- Bounce RF signal off scatterers
- Detect if something is there
  - Lots of hypotheses
- Measure how long it takes for a pulse to return
  - Ranging (and potentially angle and Doppler estimation)



RaDAR

- Radio Detection And Ranging (RaDAR)
  - Let's be glad that it has transitioned from acronym to word (radar)

- "First" "Radar"
  - Telemobiloscope: name that Christian Hülsmeyer used in his 1904 patent
  - Practically, he could not really do ranging but it would do detection
- Alexander Popov observed multipath effects caused by ships in communications in 1897
  - Invented "sensorless sensing"?

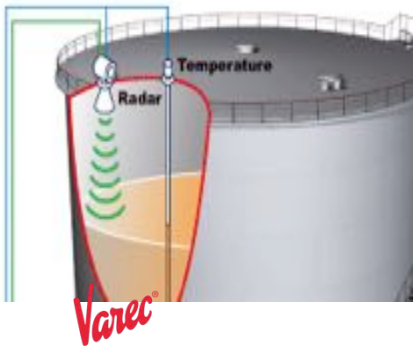
Commercialization of Radars

- **Radars are starting to show up everywhere**
  - **You'll be wearing radars soon**

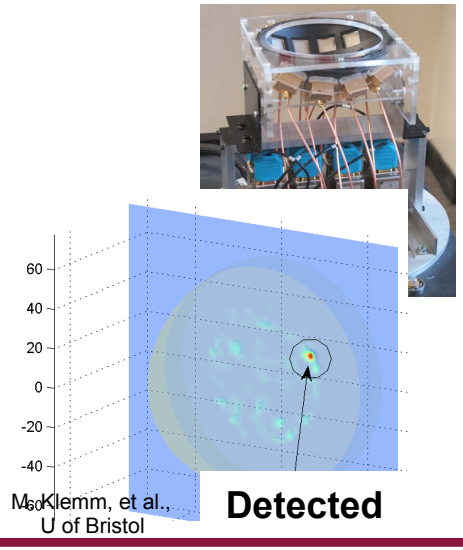
- **Dramatic reduction in costs, size, weigh, and power over the last decade**
  - **Entering the age of radar on a chip**

Active Terahertz Scanner

Radar Tank Gauge



Radar Breast Tumor Detection

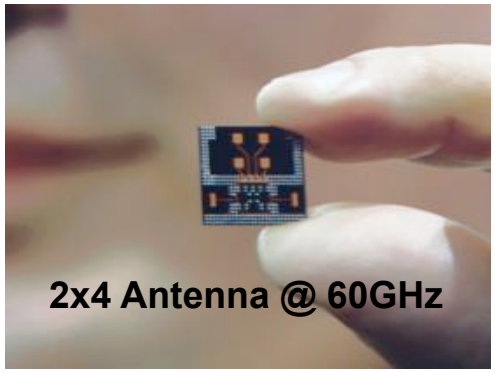


M. Klemm, et al., U of Bristol

Detected

Google ATAP's Soli

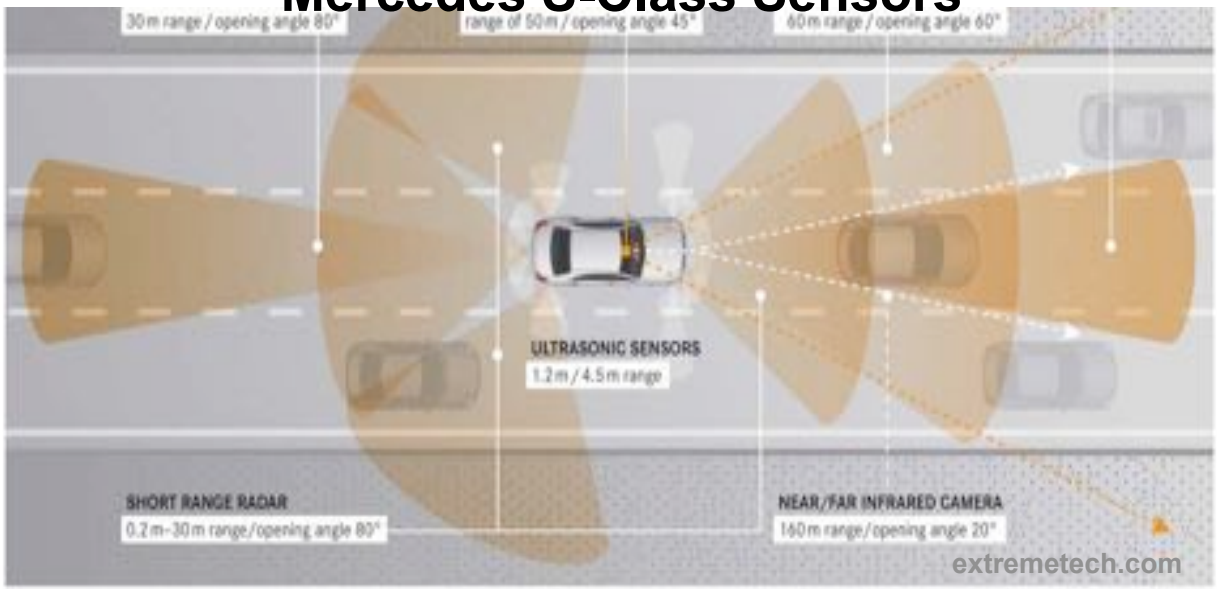
Google I/O



Vehicular Radars

- Avoid collisions
  - Driver error
  - Self driving cars
- "See" better
- Fuse with other modalities
  - Visible
  - IR
  - Lidar
  - Ultrasonics

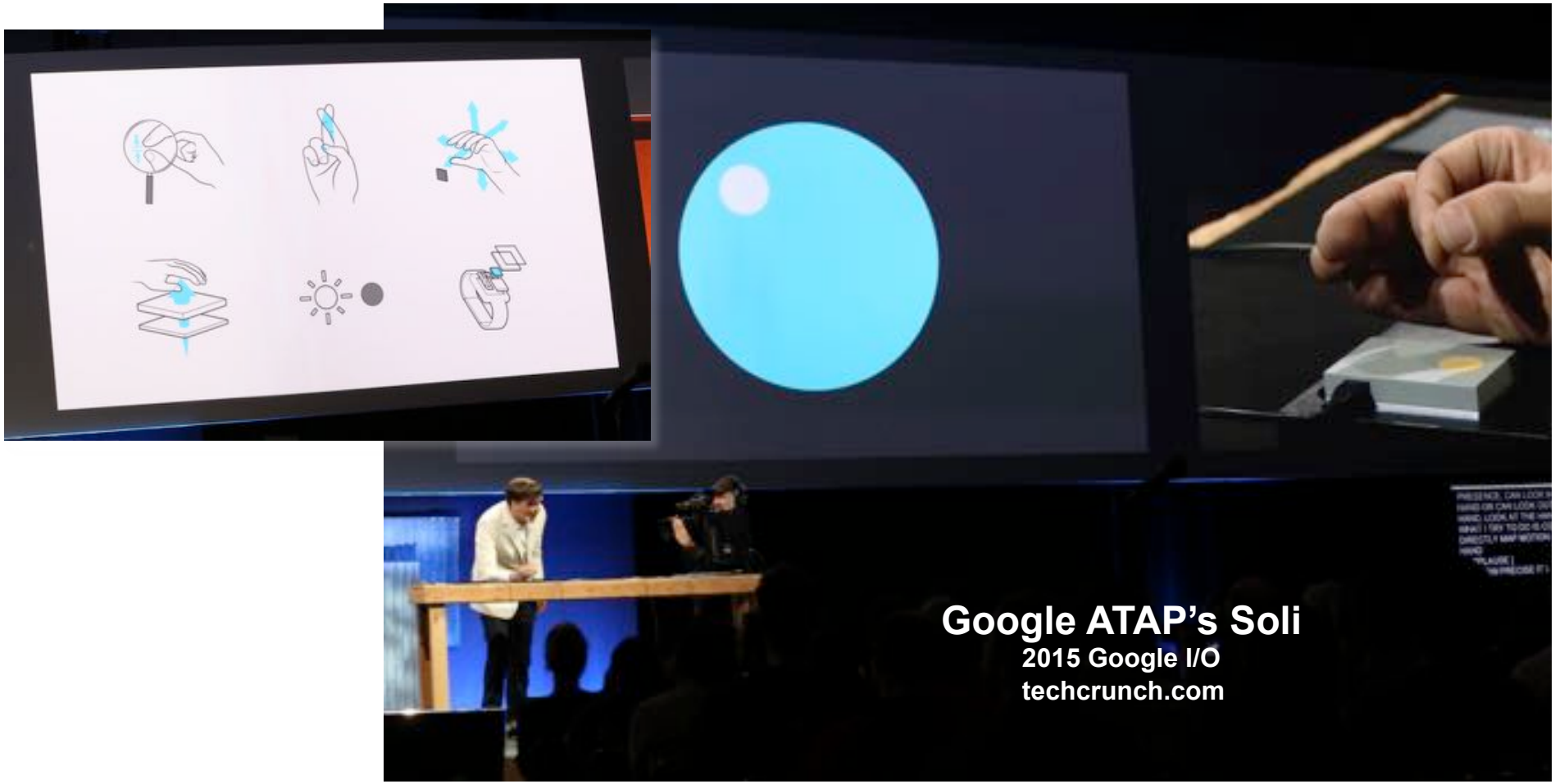
Mercedes S-Class Sensors



Google Car

Personal Radars

- **You will be using, even wearing radars soon**
  - **Gesture interface**



Topics

- Why is this guy talking about radars?
- **What do radars care about?**
- What's the problem?
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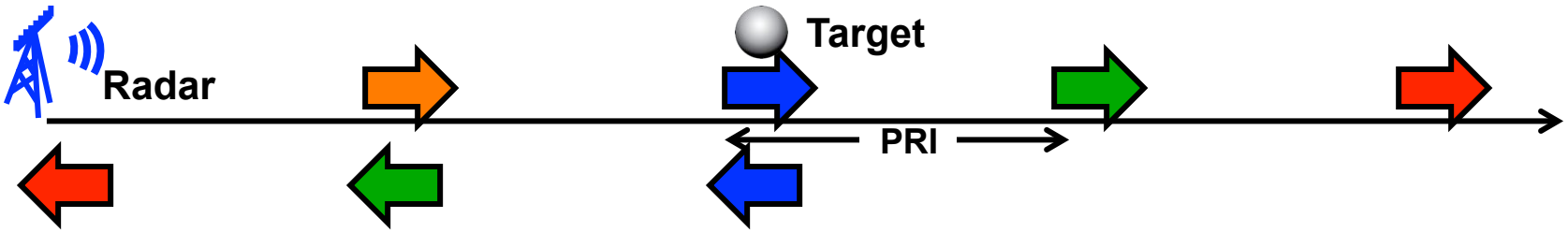
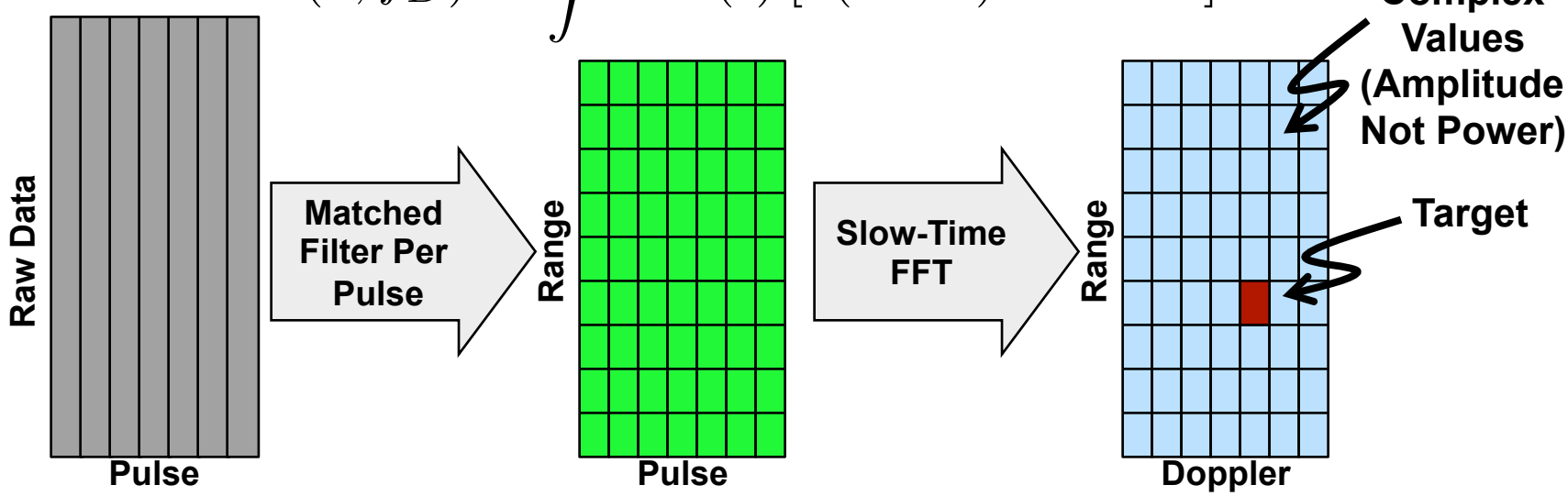
Pulse-Doppler Processing

- **Transmit sequence of short "pulses"**



- **Build matched filter for range and Doppler hypotheses**
  - **Assume that Doppler is not resolvable by a single pulse**

$$h(\tau, f_D) \propto \int dt\, z(t)\, [s(\tau - t)\, e^{i\, 2\pi\, f_D\, t}]^*$$



Radar Waveforms
Chirp

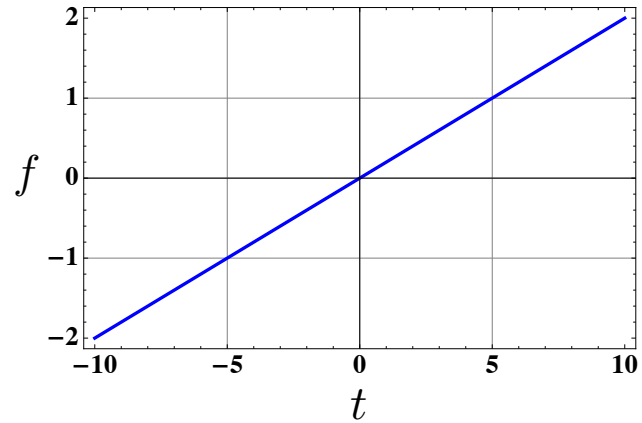
"Pulse" – Chirp

- Standard radar waveform
- Complex tone that ramps

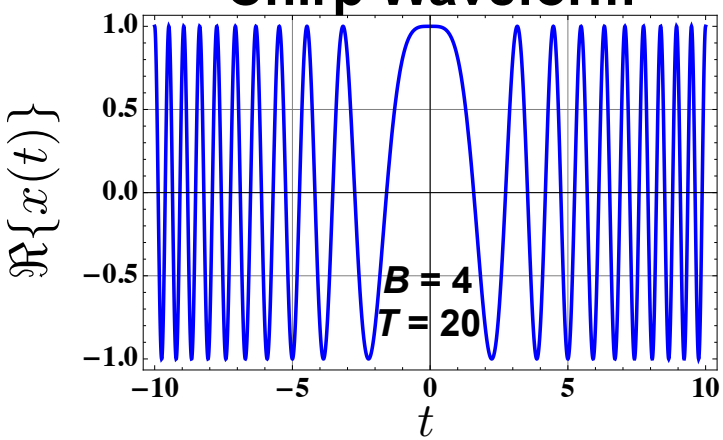
$$x(t) \propto e^{\frac{i\pi B t^2}{T}}$$

- Constant modulus
- Approximately uniform spectrum

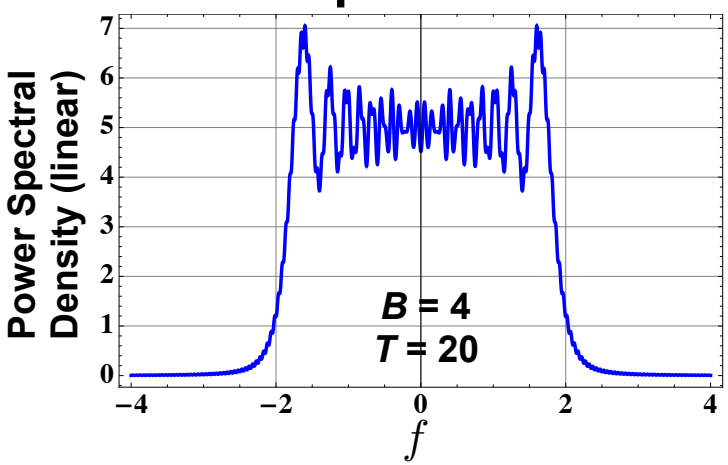
Chirp Spectral Cartoon



Chirp Waveform



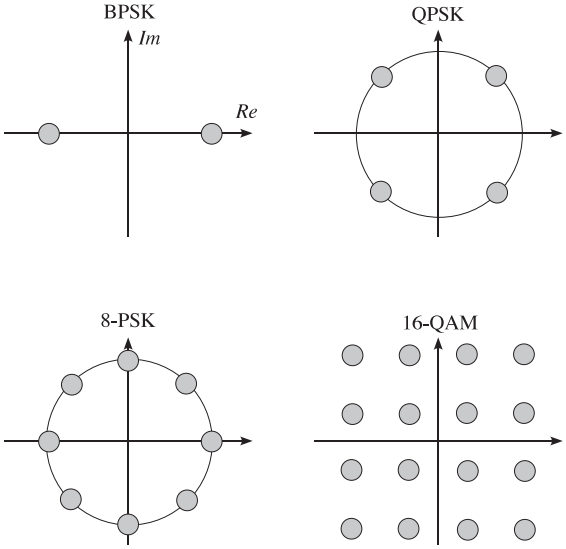
Spectrum



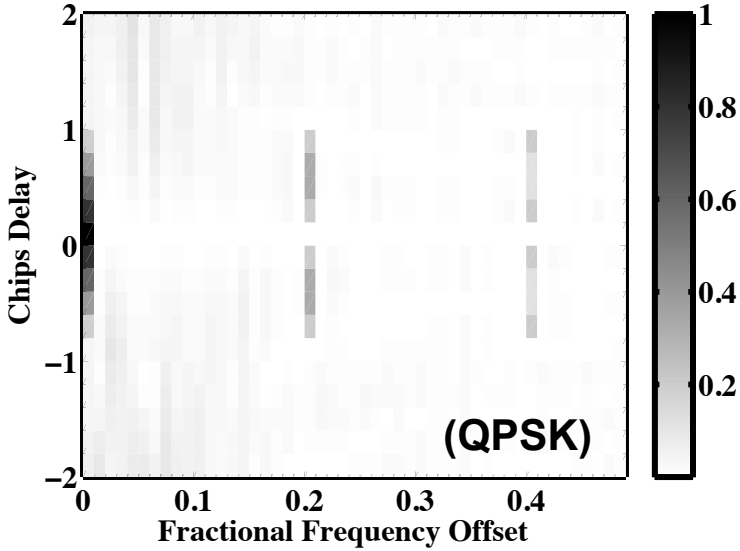
Employing Digital Modulations

- Can use communications signals for radar
  - Variety of potential concerns
    - Sidelobes
    - Clutter mitigation

Constellations



Cross Ambiguity Function

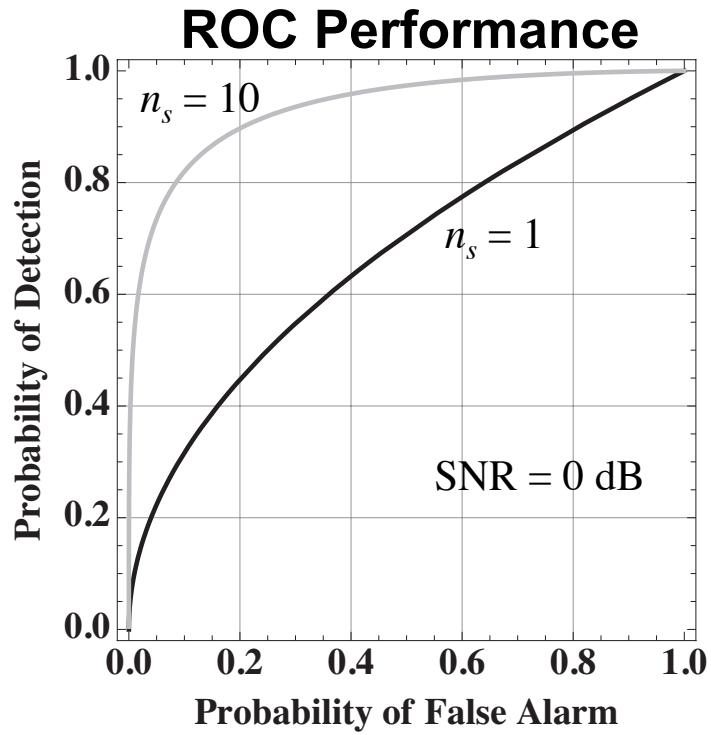


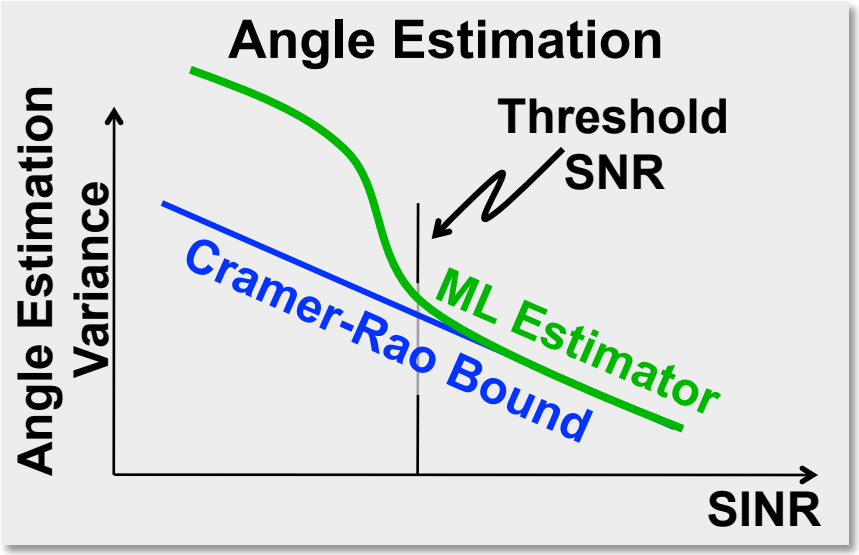
- Consider ambiguity function
  - Like a range-Doppler point spread function

$$\chi(\tau, \delta f) = \int_{-\infty}^{\infty} dt\, s(t)\, s^*(t-\tau)\, e^{i\,2\pi\,\delta f\, t}$$

Radar Performance Characterization

- **Detect targets**
  - Function of SINR
  - Presented in terms of receiver operating characteristic (ROC) performance





- **Estimate target parameters**
  - Limited by the Cramer-Rao Bound
  - Variance ~ $(B^2\ \mathrm{SINR})^{-1}$

Topics

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FCC Allocation Chart

Pressure To Release Radar Spectrum

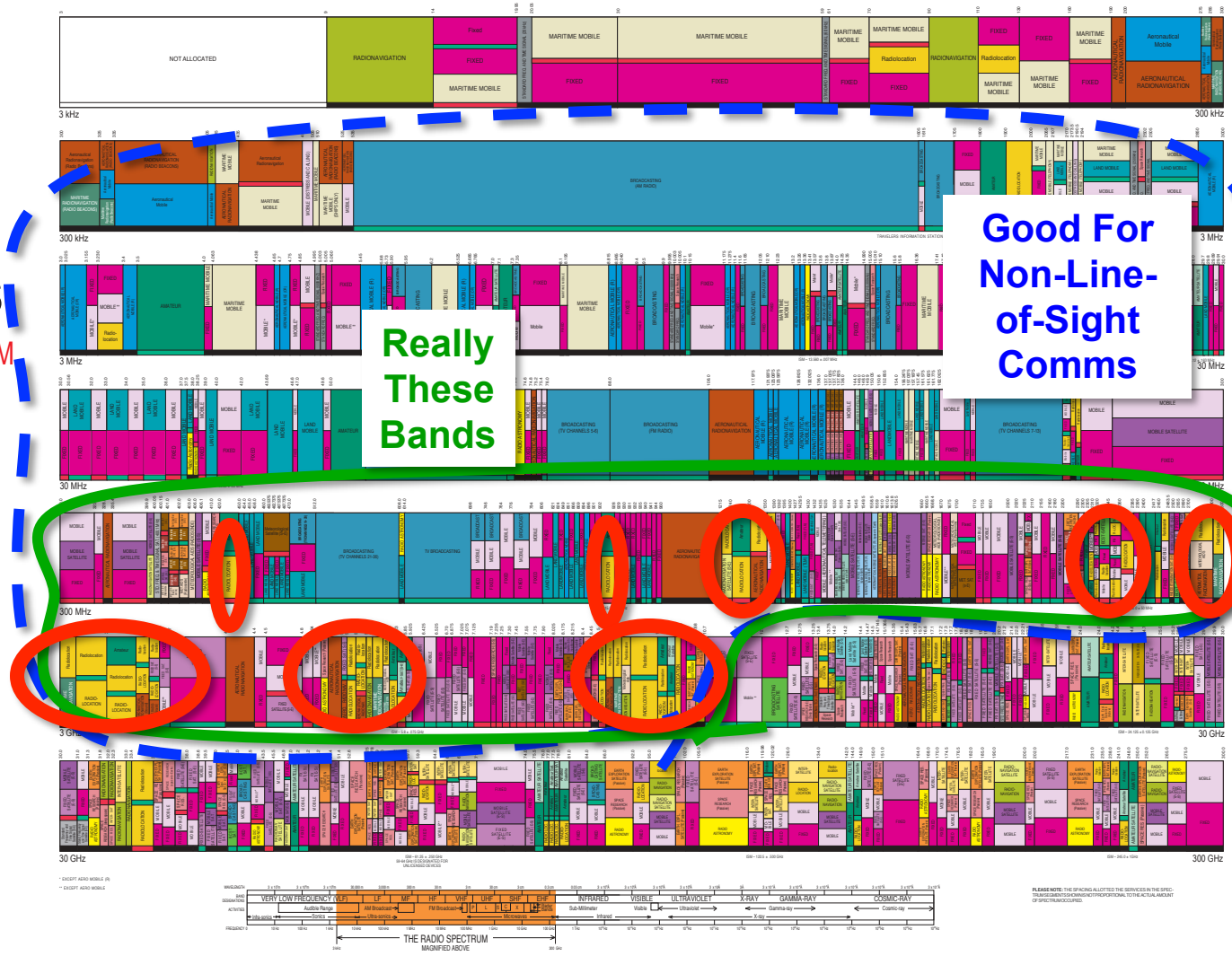
UNITED

STATES

FREQUENCY

ALLOCATIONS

THE RADIO SPECTRUM



RADIO SERVICES COLOR LEGEND

- AERONAUTICAL MOBILE
- AERONAUTICAL MOBILE SATELLITE
- AERONAUTICAL RADIONAVIGATION
- AMATEUR
- AMATEUR SATELLITE
- BROADCASTING
- BROADCASTING SATELLITE
- EARTH EXPLORATION SATELLITE
- FIXED
- FIXED SATELLITE
- INTER-SATELLITE
- LAND MOBILE
- LAND MOBILE SATELLITE
- MARITIME MOBILE
- MARITIME MOBILE SATELLITE
- MARITIME RADIONAVIGATION
- METEOROLOGICAL AIDS
- METEOROLOGICAL SATELLITE
- MOBILE
- MOBILE SATELLITE
- RADIO ASTRONOMY
- RADIODETERMINATION SATELLITE
- RADIOLOCATION
- RADIOLOCATION SATELLITE
- RADIONAVIGATION
- RADIONAVIGATION SATELLITE
- SPACE OPERATION
- SPACE RESEARCH
- STANDARD FREQUENCY AND TIME SIGNAL
- STANDARD FREQUENCY AND TIME SIGNAL SATELLITE

ACTIVITY CODE

- GOVERNMENT EXCLUSIVE
- GOVERNMENT/NON-GOVERNMENT SHARED
- NON-GOVERNMENT EXCLUSIVE

ALLOCATION USAGE DESIGNATION

SERVICE	EXAMPLE	DESCRIPTION
Primary	FIXED	Capital Letters
Secondary	Mobile	1st Capital with lower case letters

This chart is a graphic single-point-in-time portrayal of the Table of Frequency Allocations used by the FCC and NTIA. As such, it does not completely reflect all aspects, i.e., footnotes and recent changes made to the Table of Frequency Allocations. Therefore, for complete information, users should consult the Table to determine the current status of U.S. allocations.

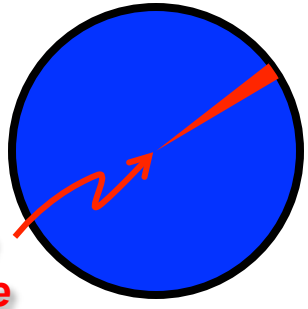
U.S. DEPARTMENT OF COMMERCE
National Telecommunications and Information Administration
Office of Spectrum Management
October 2003

PLEASE NOTE: THE SPACING ALLOTTED THE SERVICES IN THE SPECTRUM SEGMENTS BY SHOWING IT IS PROPORTIONAL TO THE ACTUAL AMOUNT OF SPECTRUM DEDICATED.

Potential Solutions
From Traditional Radar Perspective

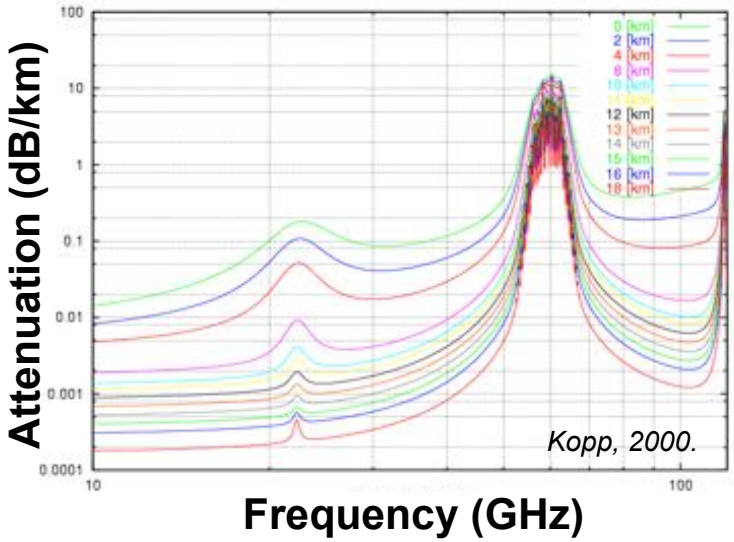
- **Don't give it to them**
  - Fighting powerful economic forces
  - U.S. does not control world's spectrum

World Telecom
1.6 Trillion/Year
Gartner, Inc. 2014.



Probably Can't See Radar Slice

Atmospheric Attenuation



- **Push radars to X-band and above**
  - Many radars are already there
  - Transmit power (complicated trade)
  - Some loss in long range propagation
  - Getting chased by comms again

- **Explore radar and radio coexistence**
  - DARPA SSPARC efforts

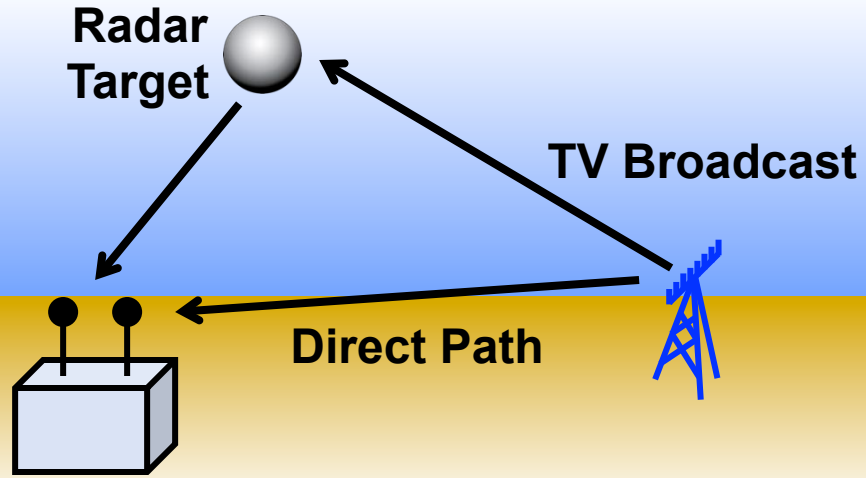
Radars Versus Radios
Some Similarities

- Emits RF energy
- Receives RF energy
- Translates RF energy into information
- More bandwidth is usually better
- Higher center frequency…
  - Smaller antennas
  - Worse propagation

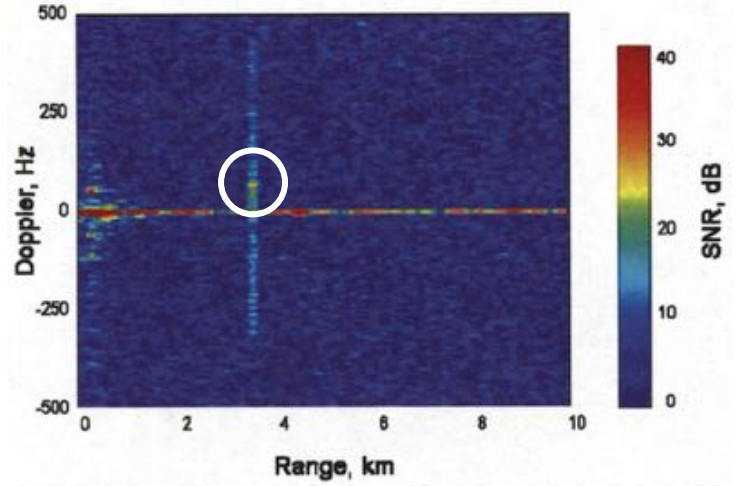
Actually, This Is an Opportunity

Passive Radar
Not Quite Cooperative Comms and Radar

- **Employ existing RF energy to locate scatterers**
  - **Classic example is TV broadcast signal**
- **Estimate broadcast signal from direct path**
- **Estimate scattering environment**



Return From Helicopter

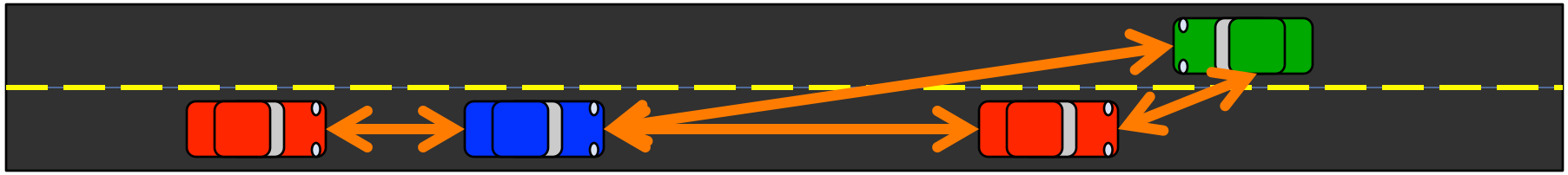


S. Carson, et al., 2006

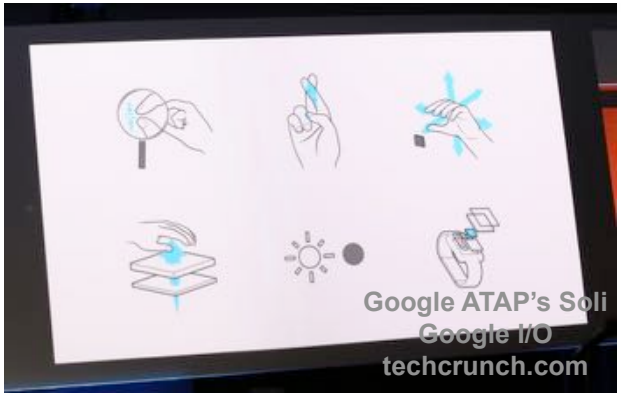
Examples of Future RF Reuse

- **Improve automobile safety**
  - Reuse same signals
  - Inter-vehicle communications
  - Collision avoidance

Google Car



- **Reuse future 28-90 GHz and 5G cellular band**
  - High data rate communications
  - Cell phone environmental awareness
  - Next generation interfaces



Topics

- Why is this guy talking about radars?
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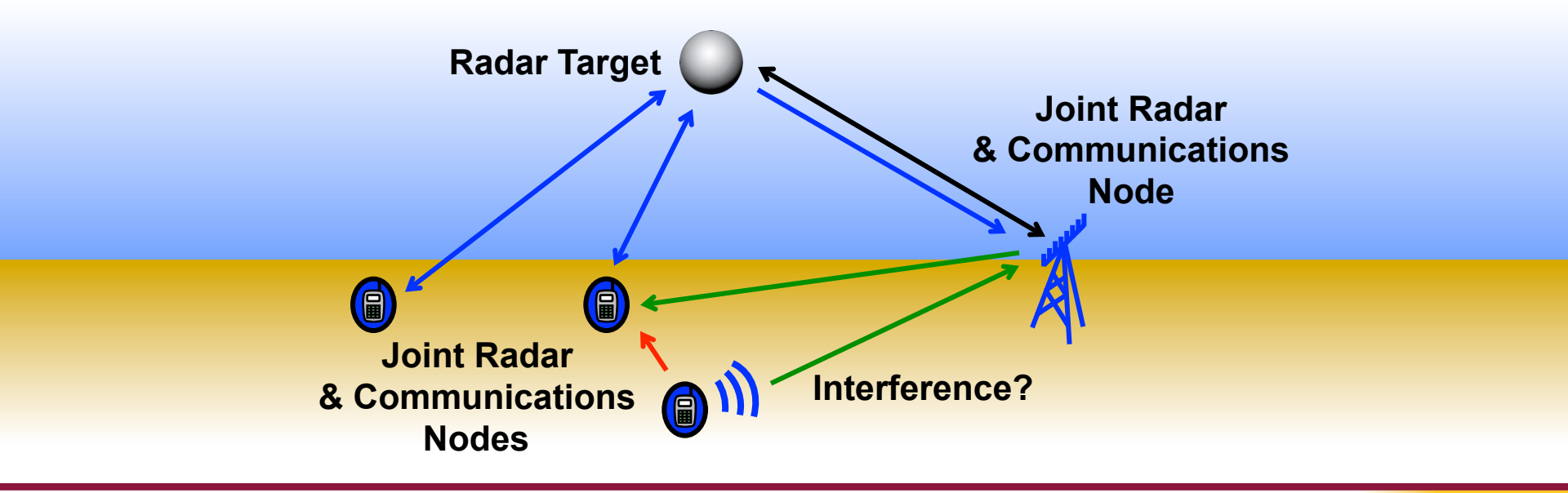
Focus of Our Current Efforts

Heterogeneous System Not Interference!
Change the Rules

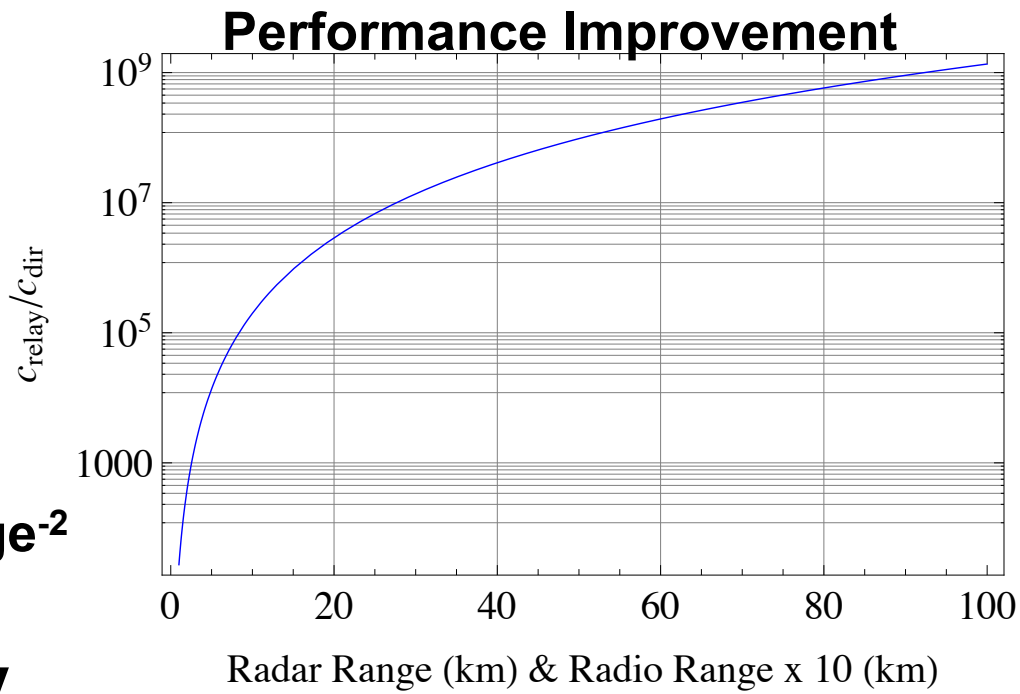
- **Assume capable nodes (radar/communications)**
  - Radios can estimate channels
  - Radars can decode and transmit communications signals
  - Radar waveform is the communications signal

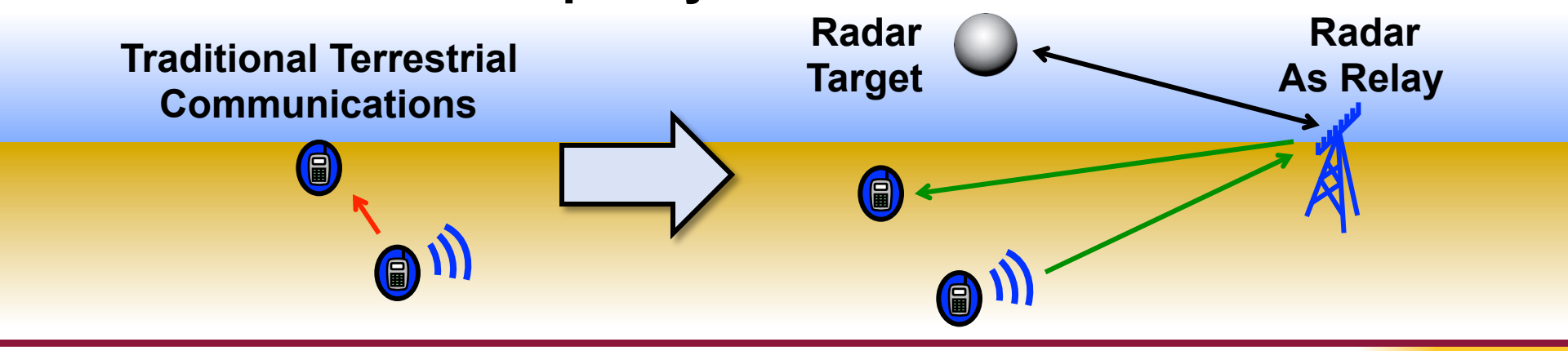
- **Estimate performance bounds**
  - Mix of information and estimation theory



Crazy Example of Potential Gains

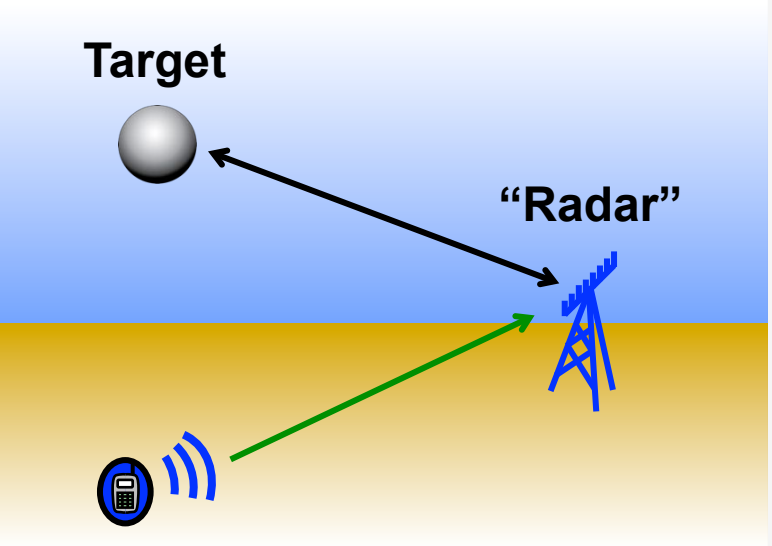
- **Use advantaged radar propagation to improve communications**
  - **Radar as a relay**
- **Assume propagation**
  - **Terrestrial comms ~range^{-4}**
  - **Radar-to-comms link ~range^{-2}**
- **Evaluate ratio of capacity**





Our Current Research

- **Find fundamental limits on joint radar target estimation and communications performance**
- **Focus on joint receiver performance as key issue**

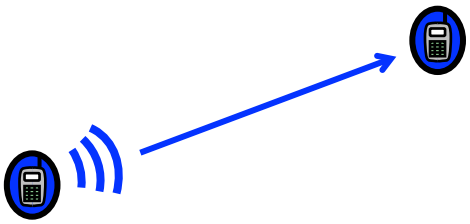


Critical Assumptions

- **Radar return and communications**
  - **Same frequency allocation**
  - **Simultaneous**
- **Radar can decode and mitigate communications signal**
- **Represent radar performance as rate**
  - **Target parameters structured random process**
  - ***Note:* radar estimation not detection**

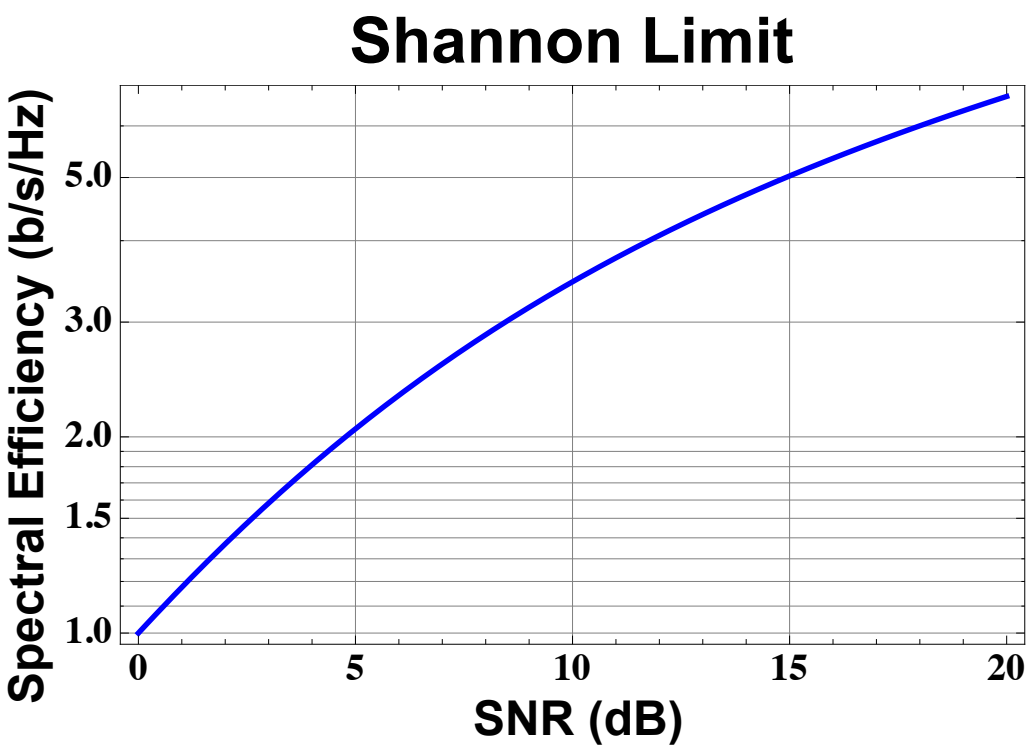
Communications Information Bound
Shannon Limit

- **Consider bound on communications on data rate**



- **Communications rate (b/s) for Gaussian signal and noise**
  - **Shannon limit**

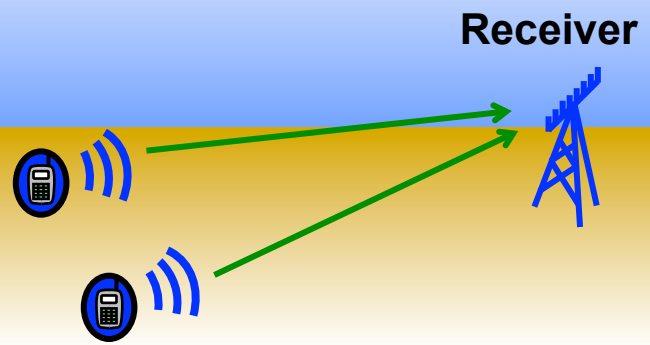
$$R_{\text{com}} \leq B \log_2\left(1 + \frac{a^2 P_{\text{com}}}{\sigma^2_{\text{noise}}}\right)$$
$$= B \log_2(1 + \text{SNR})$$



Multiple Access Communications Receiver

- Assume radar return and communications
  - Same operating band
  - Simultaneous
  - Assume all single antenna transmitters and receivers

- What is the best joint data information rate?



- This is not our problem
- This is an analogy

Multiple Access Communications Bound
Illustrative Analogy

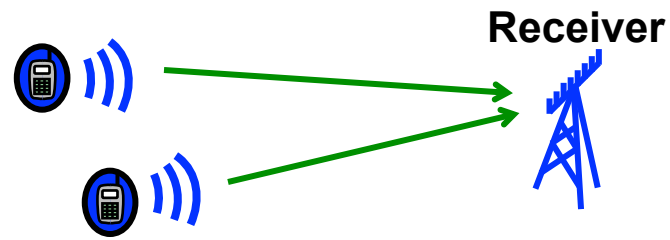
- **Satisfy all bound**

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

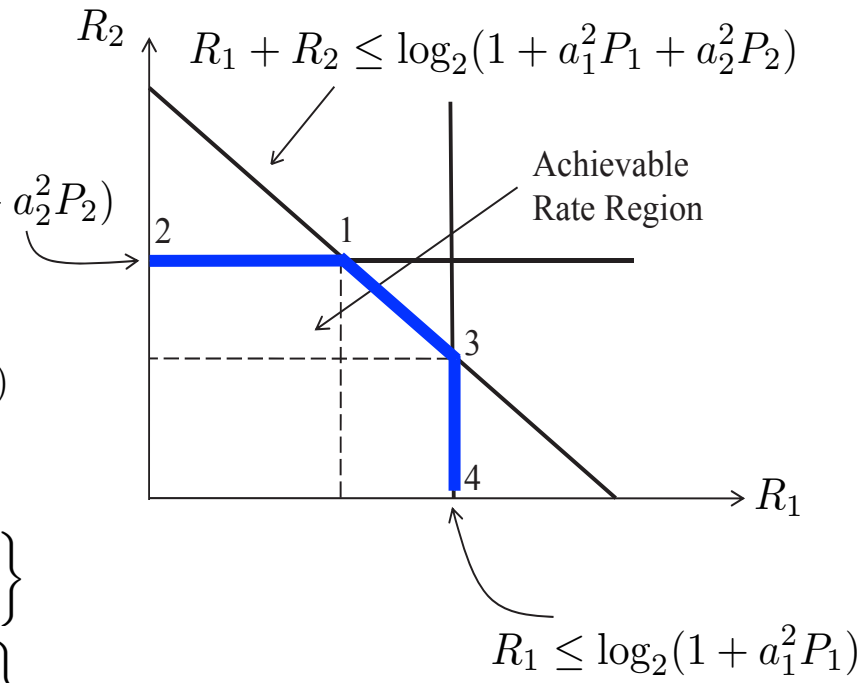
  – **Fix power of channel for both transmitters**

- **Find points of bound intersection**

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

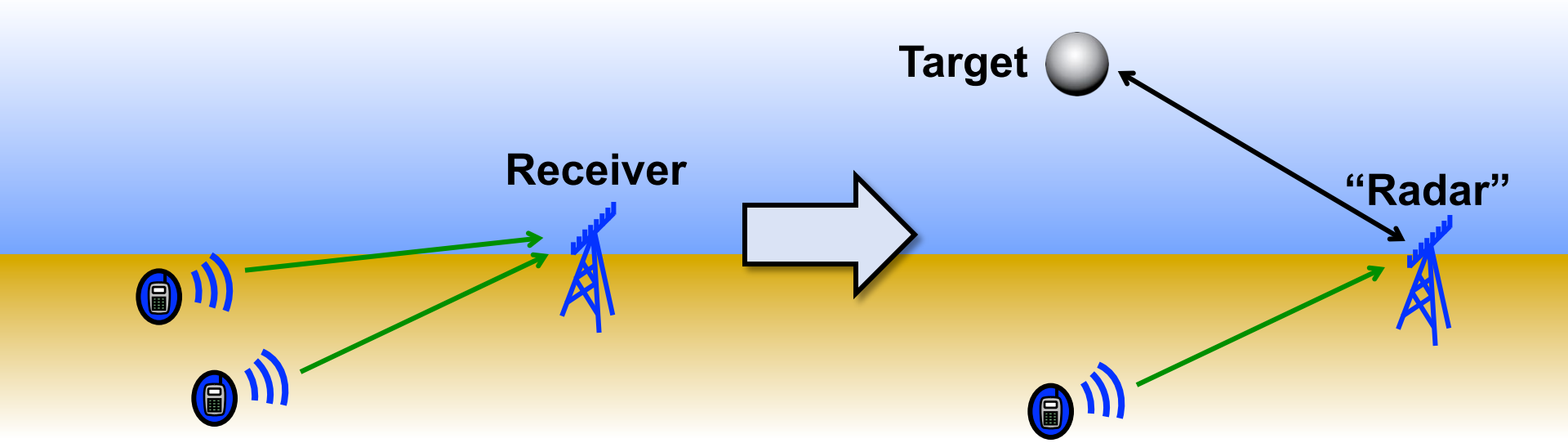


Multiple Access Bound



Multiple Access Radar/Comms Receiver
Are The Bounds Equivalent?

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

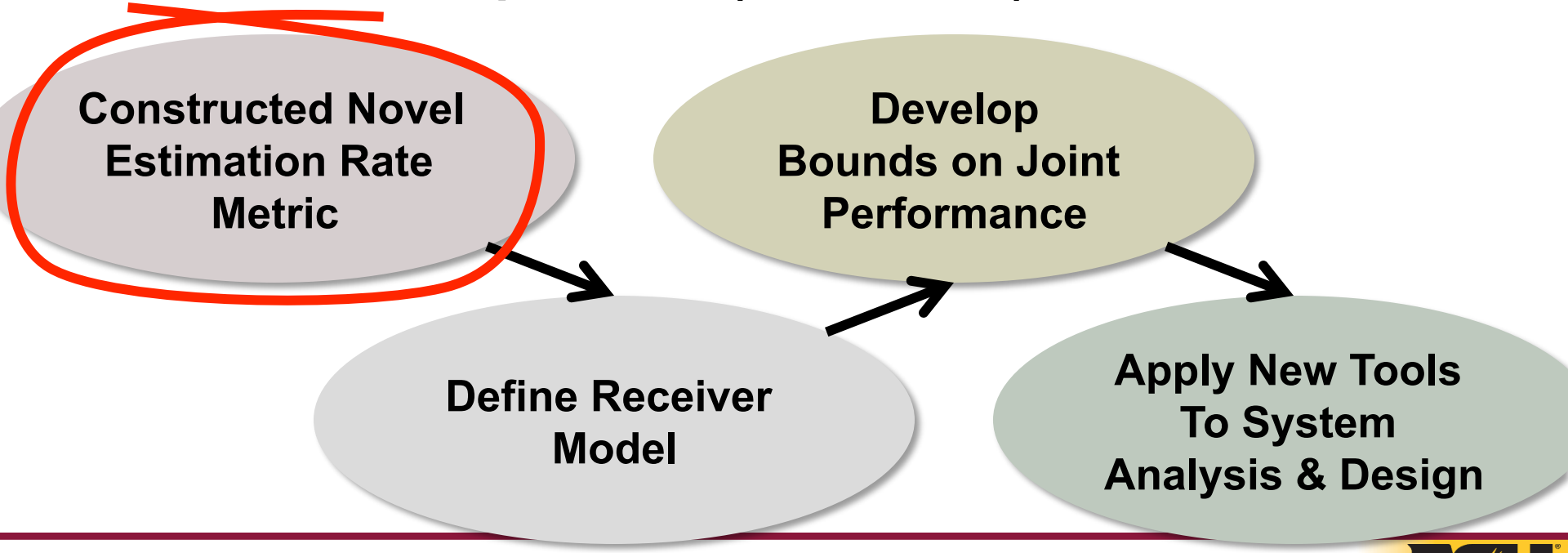


- **But, let's see how close we can get**
  - **Focus on achievable (inner) bounds**

Hint:
We Will Apply MUD to Mixed Radar and Communications

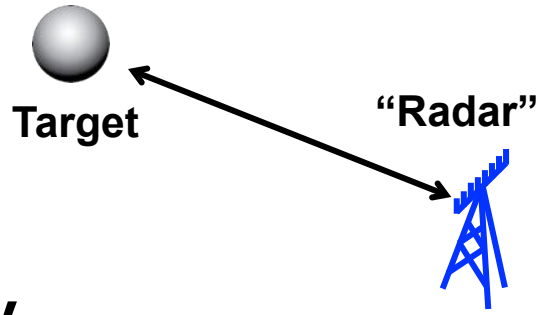
Our Approach

- Developed new formalism for analyzing joint radar and communications performance
  - Use communications multiple access channel as motivation
- Employ mix of information and estimation theory
- Construct multiple inner (achievable) bounds



Characterize Target Range Uncertainty
Random Process Characterization

- **Develop concept of estimation information rate**
- **Estimate target range (delay)**
- **Assume delay determined by partially known random process**
  - **Assume unknown delay is Gaussian**

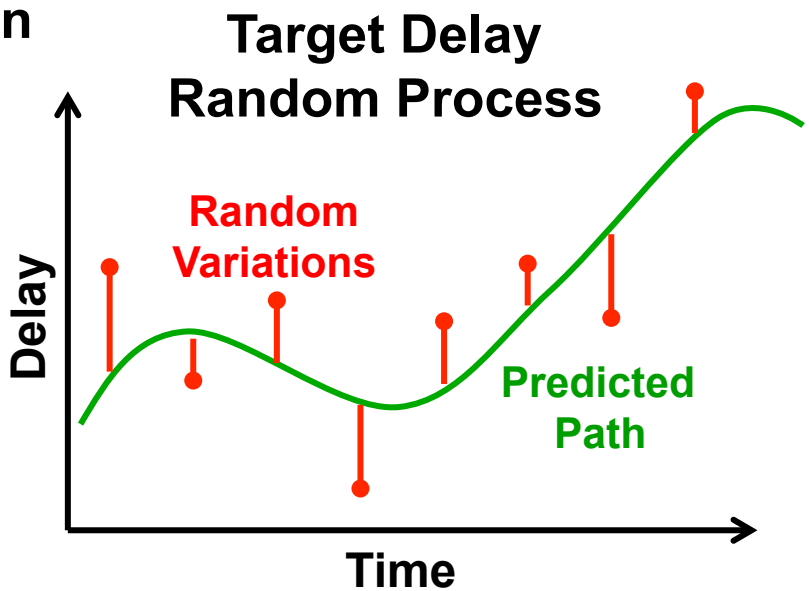


Target Delay

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

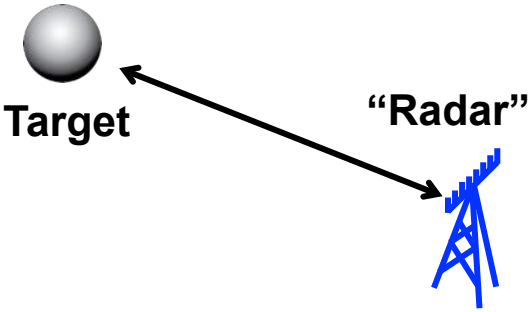
Target Delay Variance

$$\sigma_{\mathrm{proc}}^2 = \left\langle n_{\tau,\mathrm{proc}}^2 \right\rangle$$



Range (Delay) Estimation Uncertainty

- **Assume good estimator and reasonable integrated SNR**

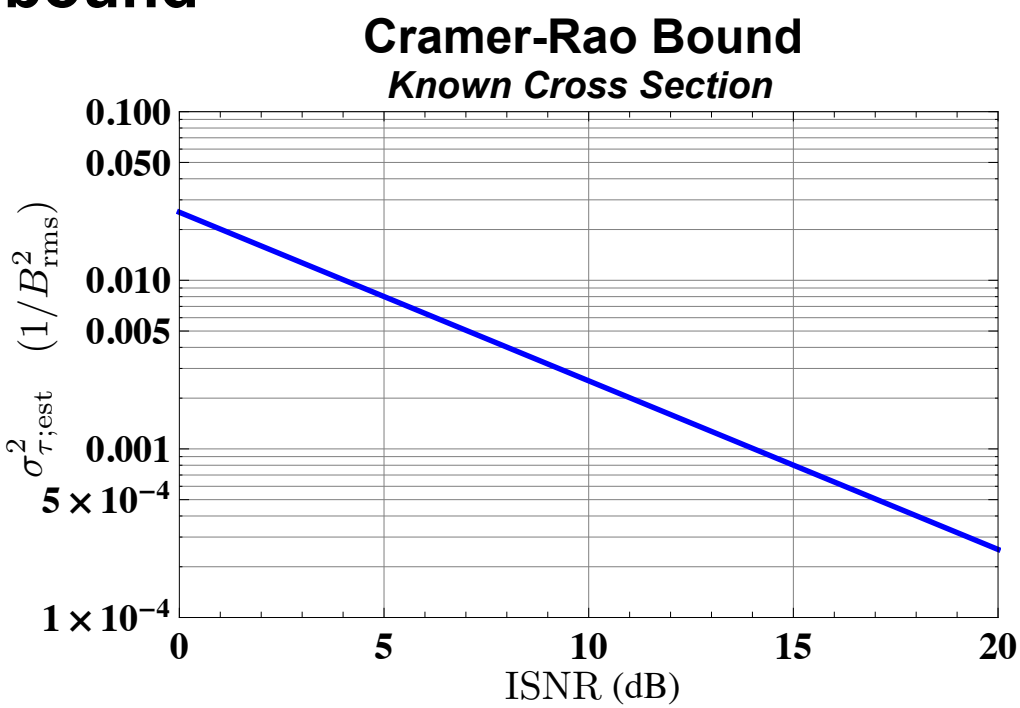


- **Use Cramer-Rao bound to get delay estimation performance bound**

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

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

$$\langle f \rangle = 0$$



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**
  - $R_{\text{est}} \sim H_{\text{uncertainty}} - H_{\text{est}}$
  - **Average number of bits required to encode estimate per unit time**

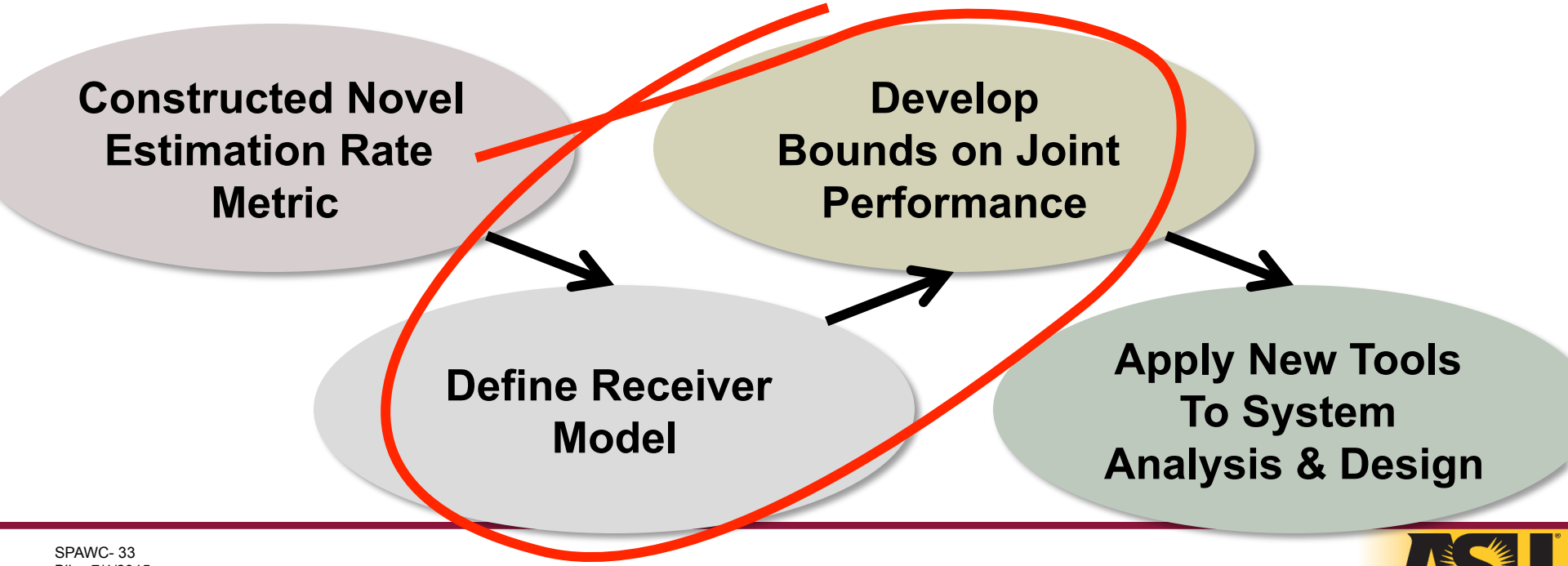
$$R_{\text{est}} \leq \sum_{m} \frac{\delta}{2T} \log_2 \left(1 + \frac{\sigma^2_{\tau_{\text{m}},\text{proc}}}{\sigma^2_{\tau_{\text{m}},\text{est}}} \right)$$

- **Ratio of variances looks like an "SNR"**

Like SNR $\dfrac{\sigma^2_{\tau,\text{proc}}}{\sigma^2_{\tau,\text{est}}}$

Our Approach

- Developed new formalism for analyzing joint radar and communications performance
  - Use communications multiple access channel as motivation
- Employ mix of information and estimation theory
- Construct novel multiple inner (achievable) bounds



Three Inner Joint Bounds
Basic Multi-Access Receiver Block

Joint Performance Bounds

- **Isolated Sub-Bands**
  - **What is done traditionally**
- **Successive Interference Cancelation**
- **Water-Filling**

Note: We Will Present Results for Single Target

Isolated Sub-band Inner Bound

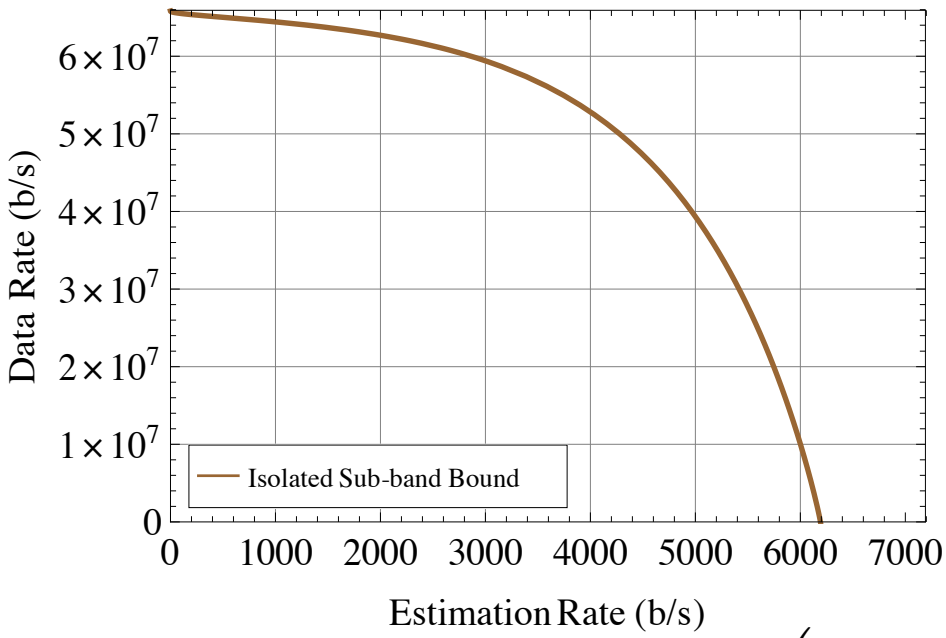
What We Do Now

- **Split spectrum B into sub-bands**
  - **Radar only**
  - **Communications only**
- **Bandwidth split determined by α**

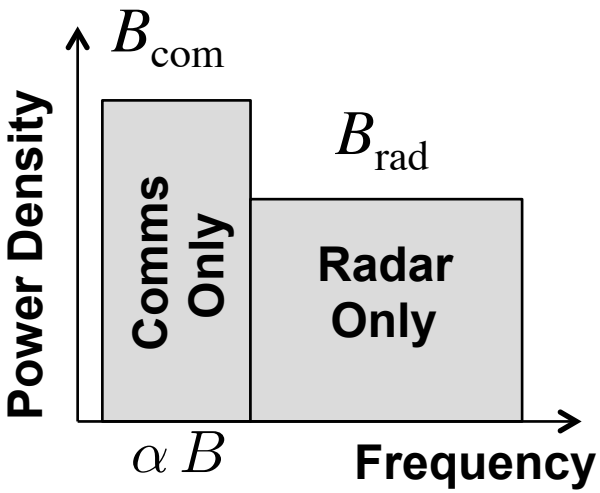
$$B = B_{\text{rad}} + B_{\text{com}}$$

$$B_{\text{com}} = \alpha\, B$$

$$R_{\text{com}} \leq B_{\text{com}} \log_2 \left[1 + \frac{b^2\, P_{\text{com}}}{k_B\, T_{\text{temp}}\, B_{\text{com}}} \right]$$



Subband Usage



$$R_{\text{est}} \leq \frac{B_{\text{rad}}}{2} \log_2 \left(1 + \frac{2\sigma_{proc}^2\, \gamma^2\, B_{\text{rad}}^2\, T\, \|a\|^2 P_{\text{rad}}}{k_B\, T_{\text{temp}}} \right)^{\delta/(T B_{\text{rad}})}$$

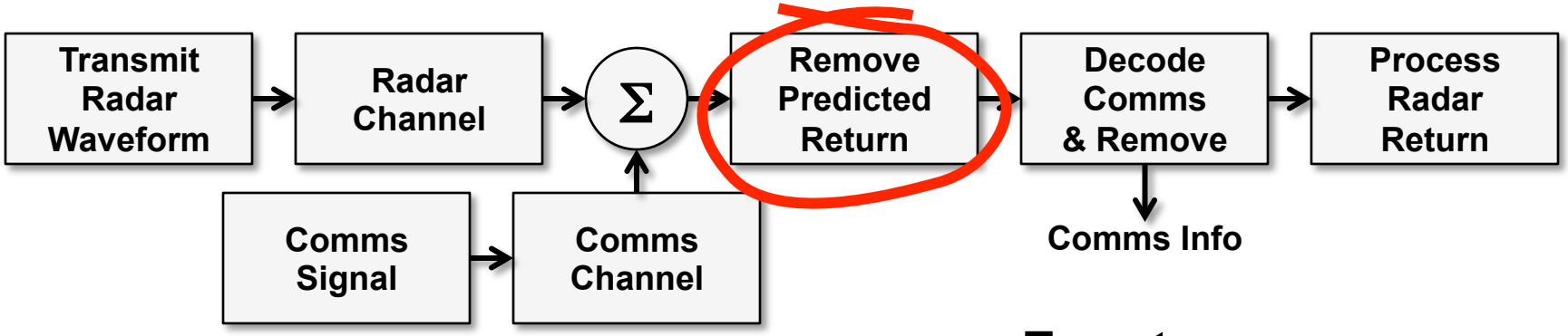
Three Inner Joint Bounds

Joint Performance Bounds

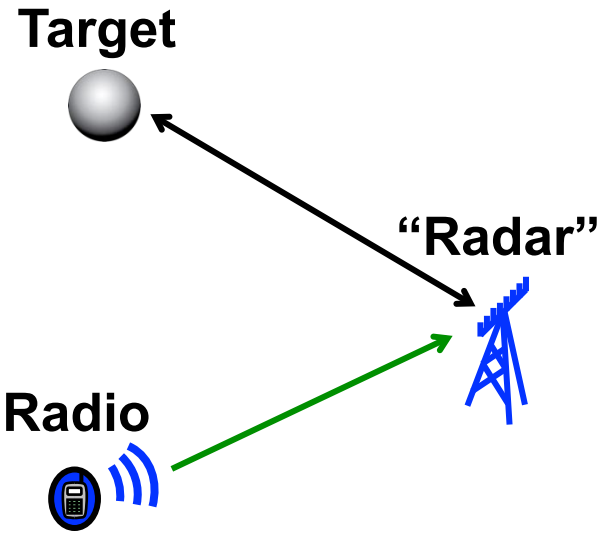
- Isolated Sub-Bands
- Successive Interference Cancelation
  - Operate communications at rate for given radar residual
  - Then, remove communications residuals
  - Operate radar without communications residuals
- Water-Filling

Bound Approach Overview
Successive Interference Cancellation

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

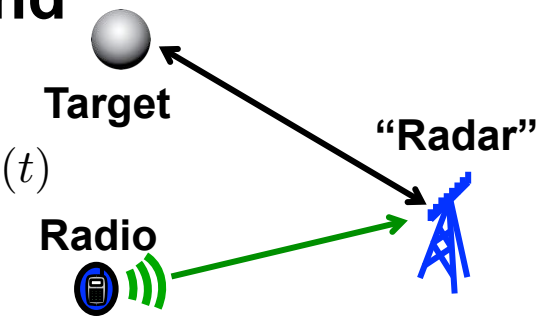


- **Basic successive interference cancellation (SIC) bound**
  - Define radar random process
  - Evaluate estimation error of radar
  - Evaluate estimation information rate
  - Evaluate communications capacity
  - Evaluate SIC point
  - Interpolate between SIC point and communications-only point



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

$$\sigma^2_{\text{int+n}} = \left\langle \|n_{\text{int+n}}\|^2 \right\rangle = P_{\text{rad}} \left(\sum_{m=1}^{N} \|a_m\|^2 (2\pi)^2 B^2_{\text{rms}} \sigma^2_{\text{proc}} \right) + \sigma^2_{\text{noise}}$$

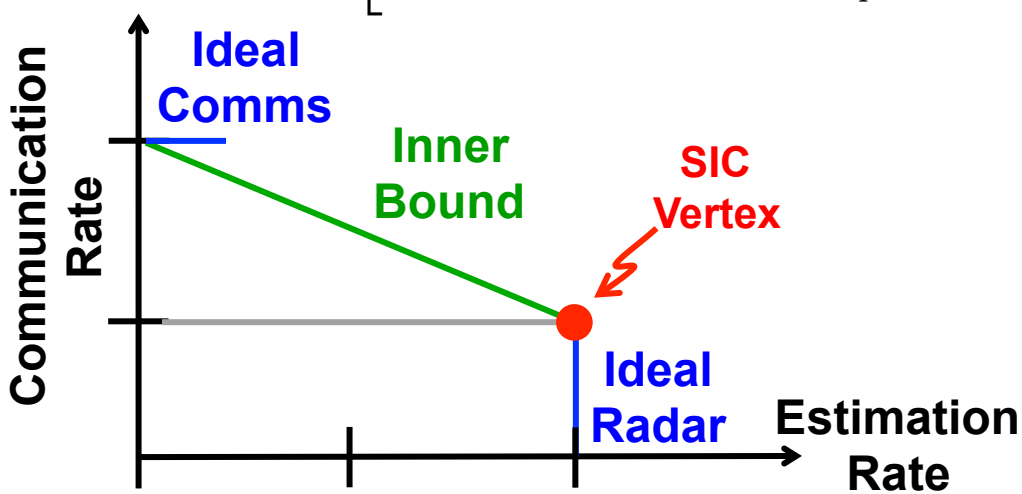
Evaluate SIC Point

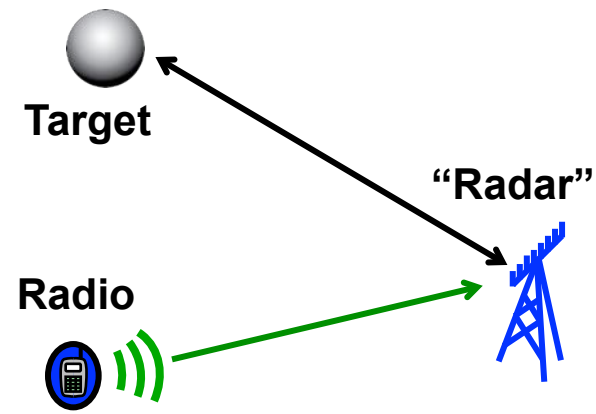
- **Find maximum communications rate such that the receiver can decode and subtract it in presence of radar return residual**

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

- **Then have ideal radar range estimation**

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





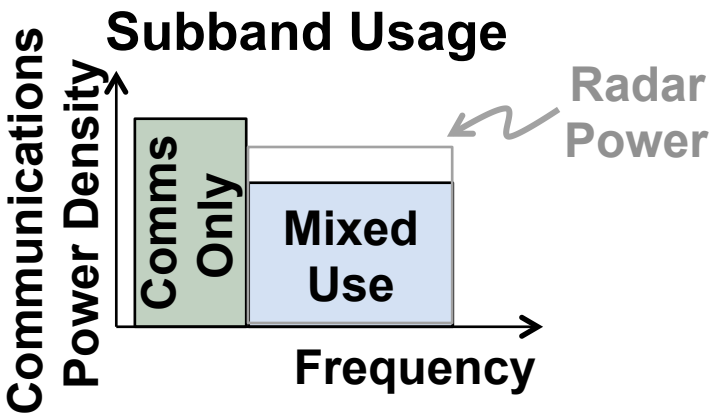
Three Inner Joint Bounds

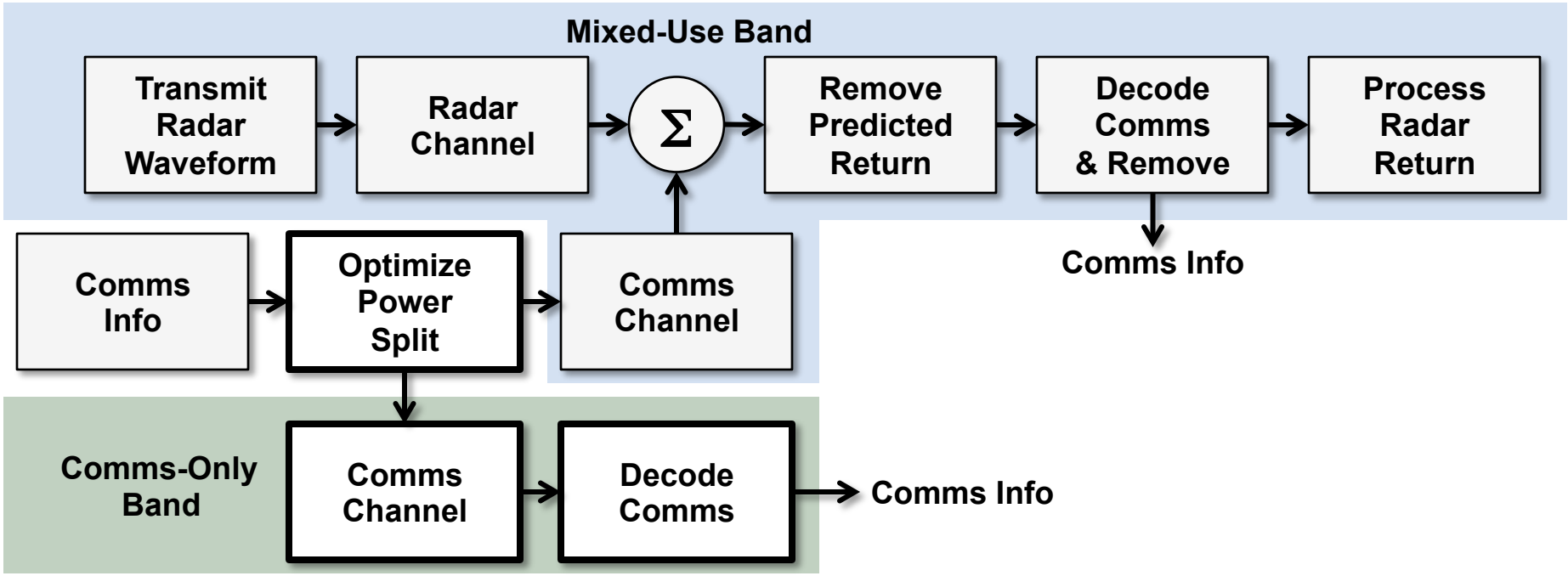
Joint Performance Bounds

- Isolated Sub-Bands
- Successive Interference Cancelation
- **Water-Filling**
  - Split bands (mixed use and communications only)
  - Split communications power and rate across subbands
  - Operate at SIC point in mixed use subband

Bound Approach Overview
Water-Filling Bound

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



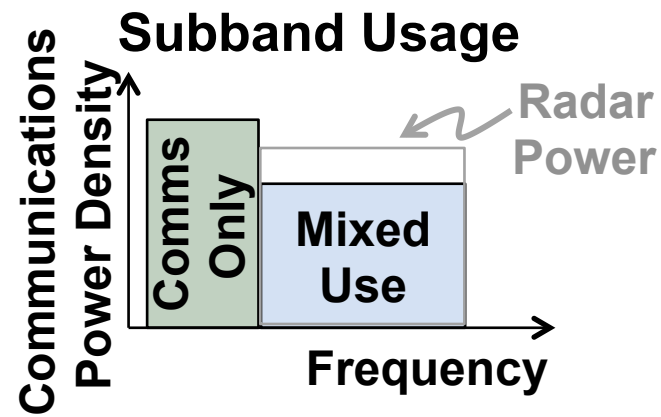


Distribute Power By "Water-Filling"

- **Optimize comms 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**

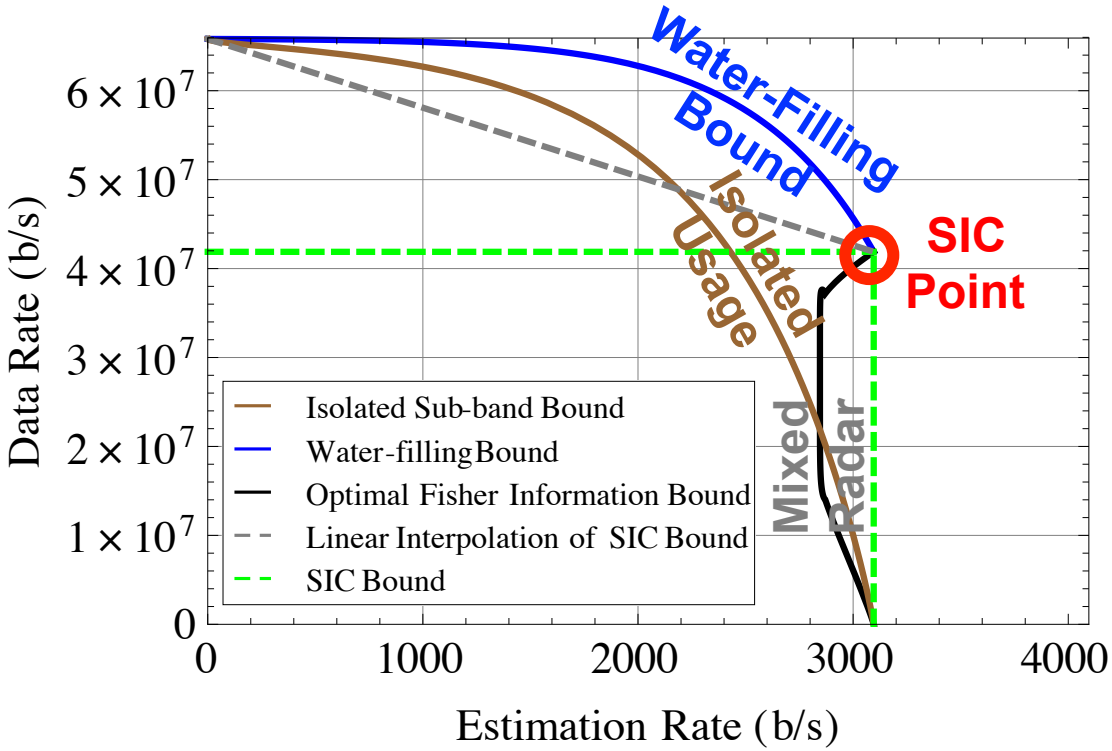
$$\mu_{\text{mix}} = \frac{b^2}{\sigma^2_{\text{int+n}}} \qquad \mu_{\text{com}} = \frac{b^2}{k_B\, T_{\text{temp}}\, B_{\text{com}}}$$

- **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

Topics

- Why is this guy talking about radars?
- What do radars care about?
- What's the problem?
- How well can you do?
- **Where do we go from here?**

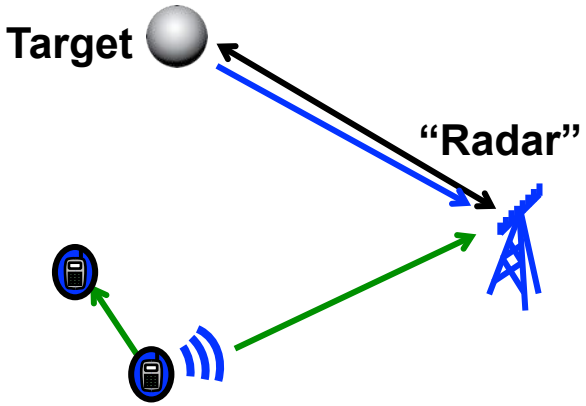
Where Are We Going?

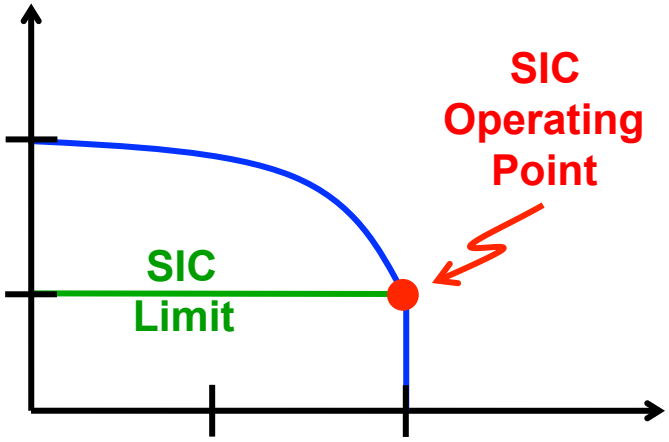
- Reuse RF energy for multiple purposes
  - It's green
  - It's cognitive
- Lots of room to improve basic theory
  - We are working on a number of issues
  - The bounds work is far from finished
  - Joint information, estimation, and detection theory
- Lots of room for system design and analysis
  - What does real systems look like?
  - Some require simultaneous transmit and receive
- Lots of room to consider partially cooperative approaches

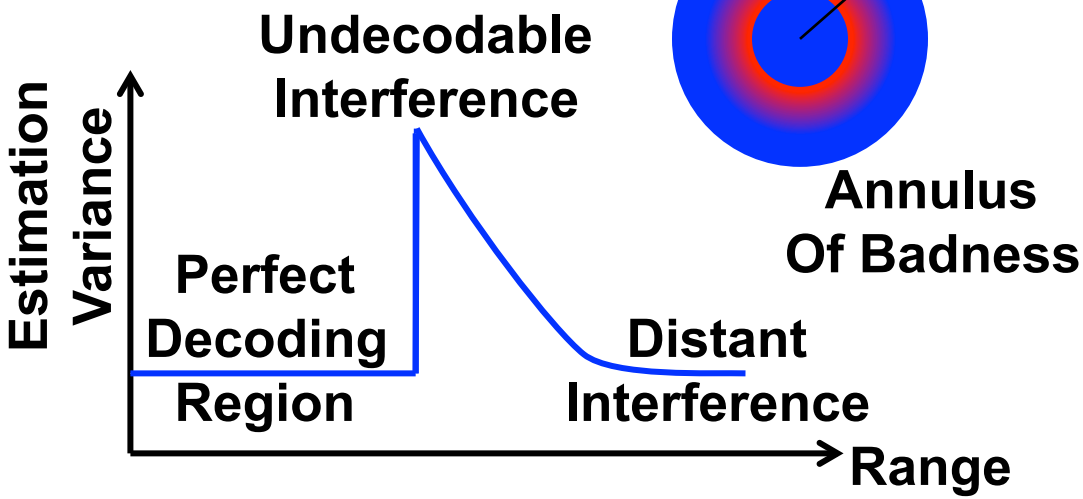
Annulus of "Badness"

Non-Cooperative Implication Simple Example

- **Region of range to communications node that maximizes adverse affect**
- **Assume advanced radar receiver**
  - **Tries to mitigate interference**
- **Communications is not radar-aware**
  - **Vary range to comms transmitter**







Some of Our Literature

- D. Bliss, "Cooperative radar and communications signaling: the estimation and information theory odd couple," *in IEEE Radar Conference*, May 2014.
- B. Paul and D. W. Bliss, "Extending Joint Radar-Communications Bounds for FMCW Radar with Doppler Estimation," *IEEE International Radar Conference*, May, 2015.
- 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*, *under review*.
- Upcoming conference papers…
- Submitting journal papers

Not Really Connected To This Talk, But You Should Buy It Anyway