IEEE VTS

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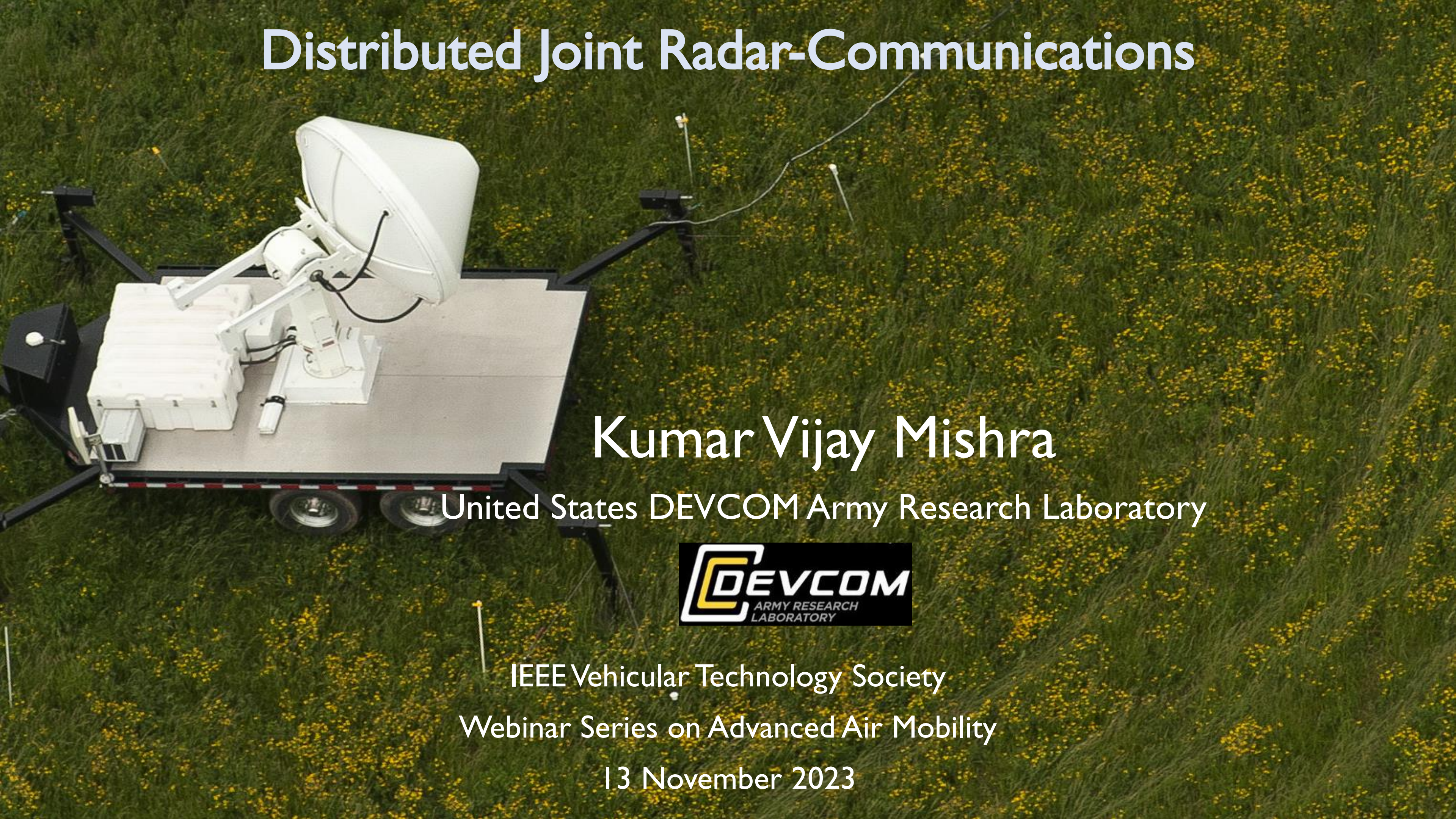
WEBINAR SERIES ON ADVANCED MOBILITY

Acknowledgement

The presenter wishes to acknowledge the IEEE Vehicular Technology Society for their sponsorship of the Webinar Series on Advanced Air Mobility.



Distributed Joint Radar-Communications

Kumar Vijay Mishra

United States DEVCOM Army Research Laboratory

DEVCOM ARMY RESEARCH LABORATORY

IEEE Vehicular Technology Society

Webinar Series on Advanced Air Mobility

13 November 2023

About the speaker

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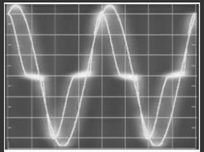
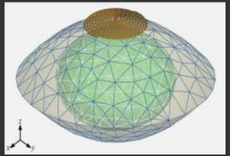
- Research Fellow, SnT, U of Luxembourg
- Technical Advisor: Hertzwell, Singapore; Aura Intelligent Systems, Boston
- Vice-Chair, URSI Commission C
- Editor, IEEE Transactions on Aerospace and Electronic Systems
- Vice-Chair, IEEE Synthetic Aperture Standards Committee; Member, IEEE SPS SAM, SPS TWG on Synthetic Apertures, INGR IEEE International Network Generations Roadmap, AESS Radar Systems Panel
- Founding member, IEEE ComSoc ISAC ETI
- Research Interests:

Radar



Signal Processing



Electromagnetics

Communications

Remote Sensing

HERTZWELL

DEVCOM ARMY RESEARCH LABORATORY

uni.lu UNIVERSITÉ DU LUXEMBOURG

AURA INTELLIGENT SYSTEMS

Courtesy: For All Mankind (S02E01)

Acknowledgements

- ARL: Brian M. Sadler
- U of Luxembourg: M. R. Bhavani Shankar, Bjorn Ottersten, Ahmet M. Elbir
- U of Texas, Dallas: Mohammad Saquib, Jiawei Liu
- UIS Colombia: Henry Arguello, Edwin Vargas, Roman Jacome, Jonathan Arley

Research was sponsored by the Army Research Laboratory and was accomplished under Cooperative Agreement Number W911NF-21-2-0288.

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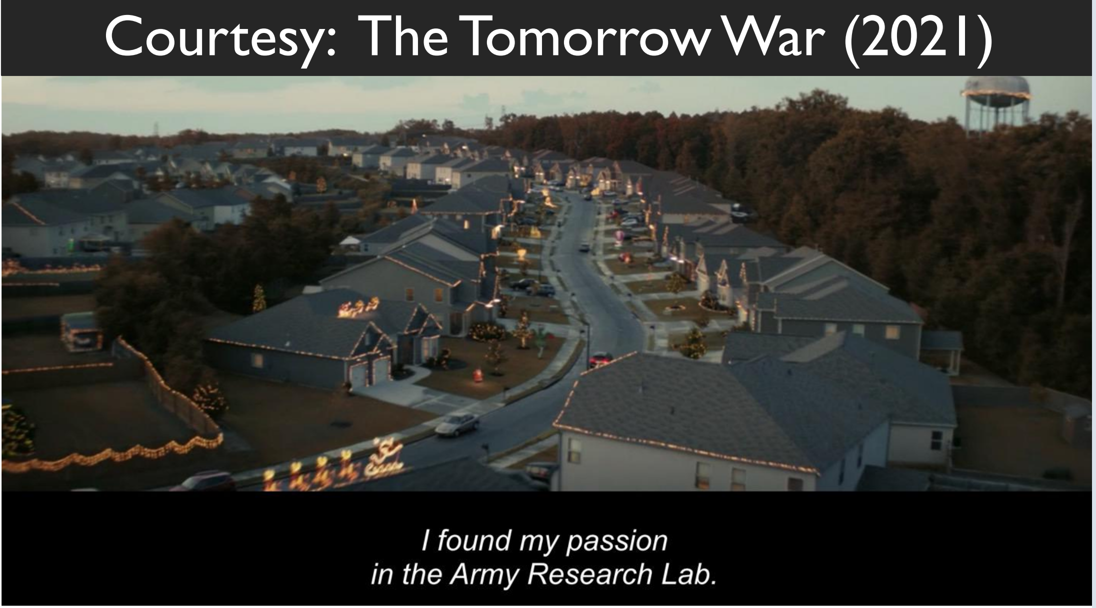
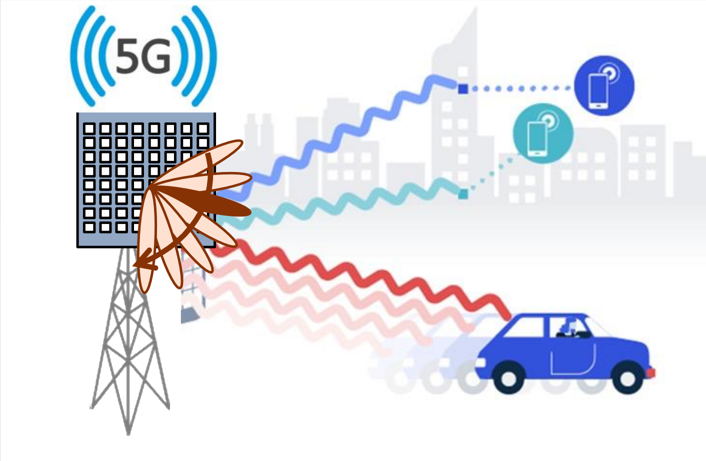
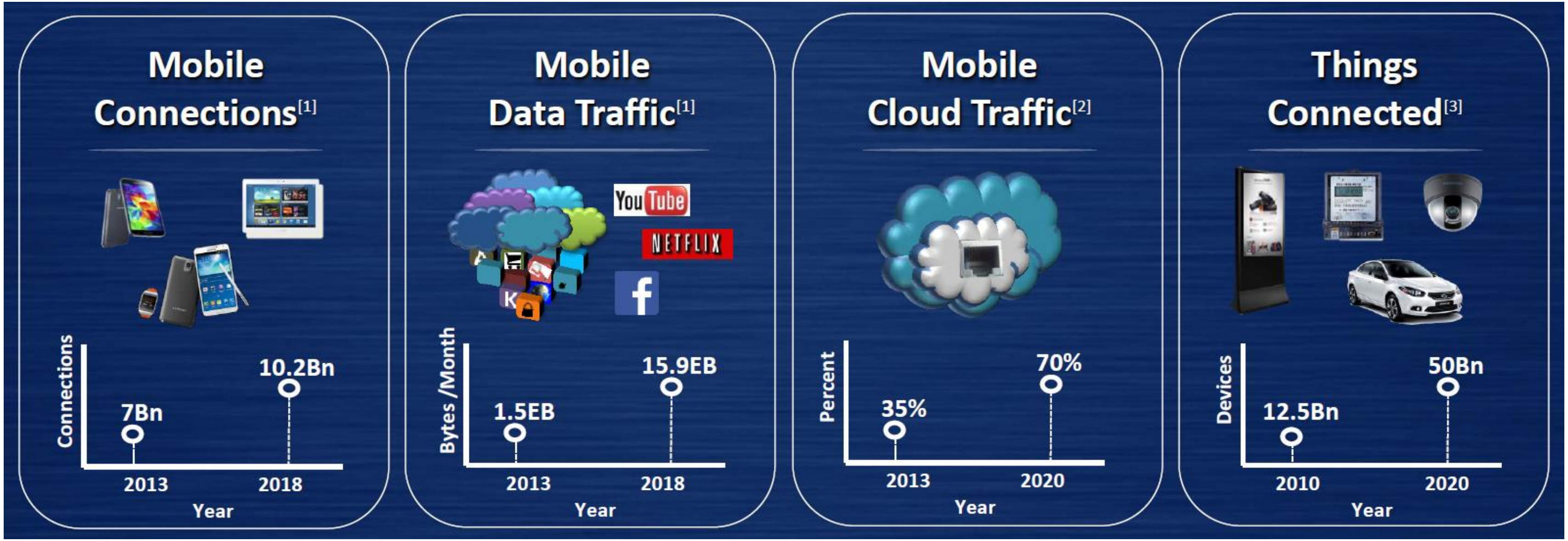

Courtesy: The Tomorrow War (2021)
I found my passion
in the Army Research Lab.


5G

Motivation

Wireless Communications Trends



- Increasing number of connected devices
- Increasing demand in high quality wireless services

[1] VNI Global Mobile Data Traffic Forecast 2013-2018, Cisco, 2014

[2] The Mobile Economy, GSMA, 2014

[3] Internet of Things, Cisco, 2013

EB (Exa Bytes) = 1,000,000 TB (Tera Bytes)

Bn= Billions

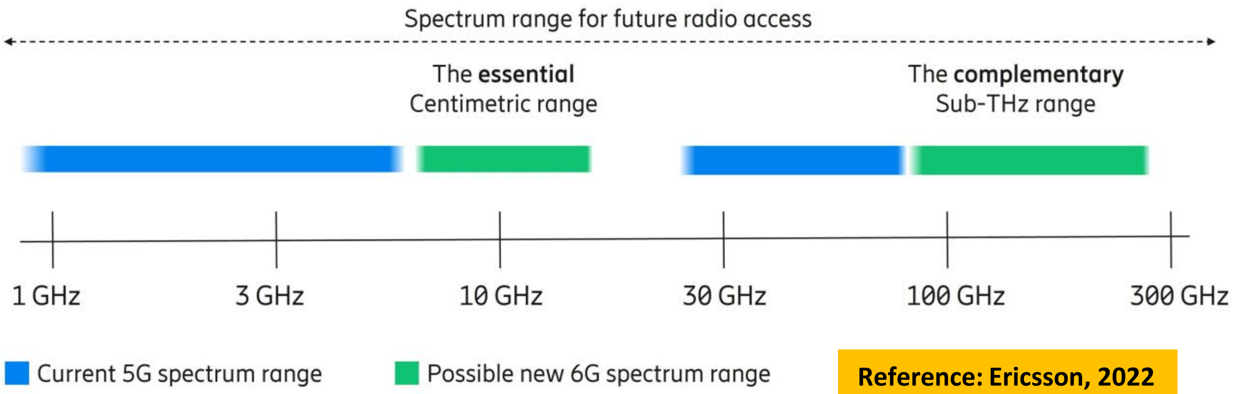
How to Meet Demand in Current Landscape?

Measure for Throughput : Shannon formula as a guide

$$C = n\, W \log(1 + \mathrm{SINR})$$

Bandwidth W

- Higher the better → Linear dependence
- Depends on spectrum allocation
- Natural resource, scarce
- Not everything is useful, expensive
- Maximize the spectral efficiency bits/sec/ Hz



Reference: Ericsson, 2022

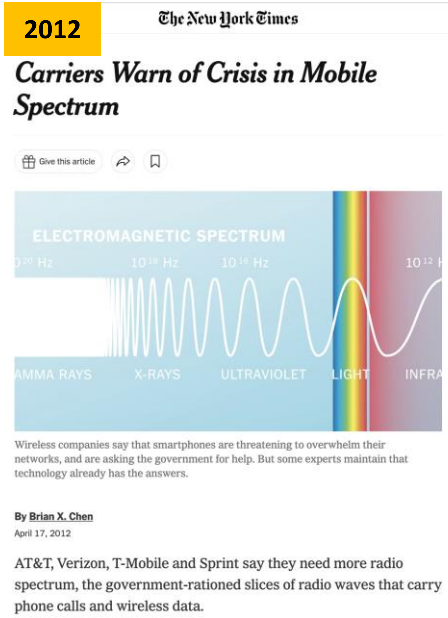
1986

The New York Times

PLAN TO REALLOCATE PART OF RADIO BAND DISPUTED

By Reginald Stuart, Special To the New York Times

July 6, 1986



2012

The New York Times

Carriers Warn of Crisis in Mobile Spectrum

Give this article

ELECTROMAGNETIC SPECTRUM

Wireless companies say that smartphones are threatening to overwhelm their networks, and are asking the government for help. But some experts maintain that technology already has the answers.

By Brian X. Chen

April 17, 2012

AT&T, Verizon, T-Mobile and Sprint say they need more radio spectrum, the government-rationed slices of radio waves that carry phone calls and wireless data.

2021

Bloomberg Wealth

Wealth

Billionaires Musk, Ergen and Dell Brawling Over Spectrum at FCC

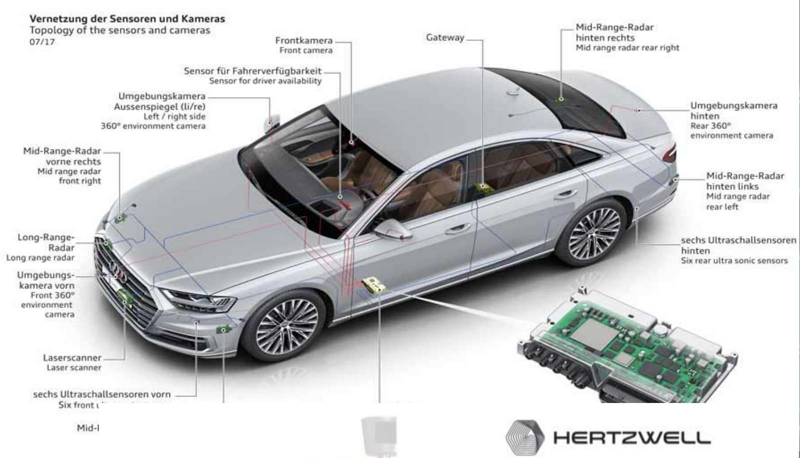
By Todd Shields + Follow

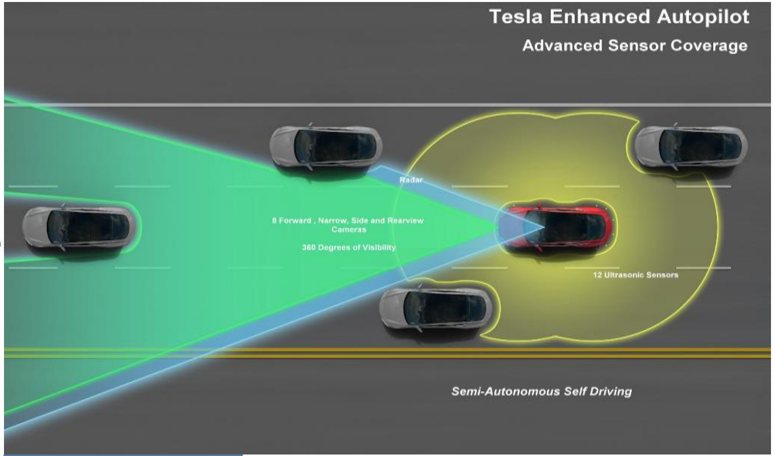
October 9, 2021, 8:45 AM EDT

- Fight boils over for spectrum needed for proposed 5G service
- Disagreement on whether service would foul SpaceX signals

Sensor-Driven Vehicles

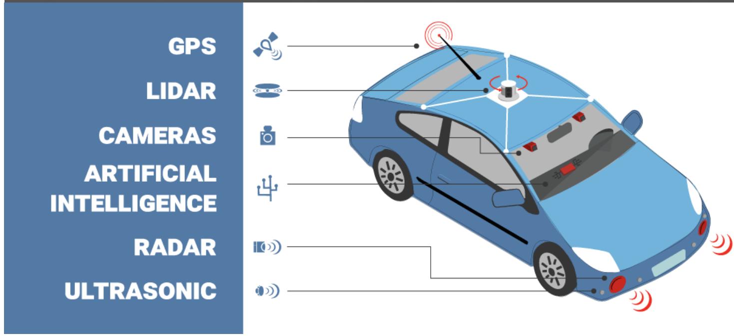
(1)





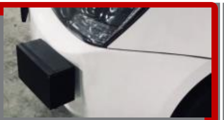
(2)

(3)



(4)

Automotive Sensors

Parameter	RADAR 	LIDAR 	Camera 
Nature	Active	Active	Passive
Range	Long Upto 250m	Mid-range Upto 100m	Near range Upto 15-20m
Accuracy	• Descent • 0.1 m, • ±0.1 m/s • H/V-FOV 30/50	• Good • 0.02 m • 0.1deg • 360deg H-FOV	• Good • Recognition at 15m
Observations	• Robust to harsh conditions • Detecting Doppler • Low cost • Lack of semantic information	• High Accuracy • 3D Mapping • High cost	• Semantic information • Poor performance in adverse weather, night • No Doppler information

In Addition, Modern Cars are …

Software-Managed

… and Connected!

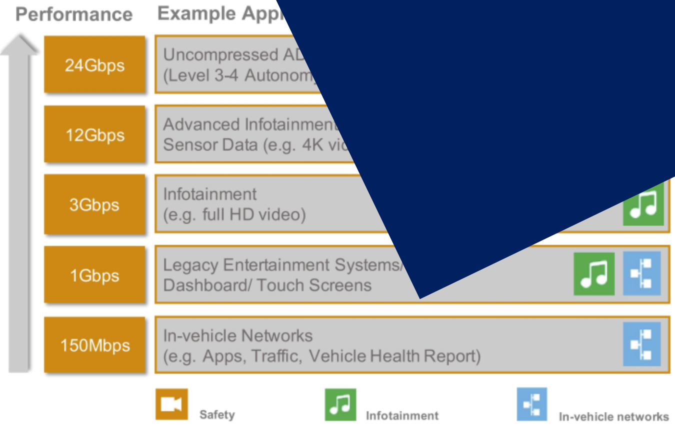
Autonomous Vehicles need high BW

1) To sense accurately

2) To stay connected

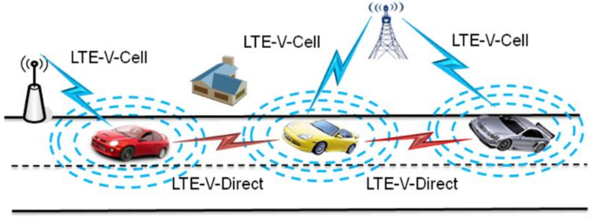
Q: Where is the BW?

…ata!



…ss technologies

- DSRC
- C-V2X

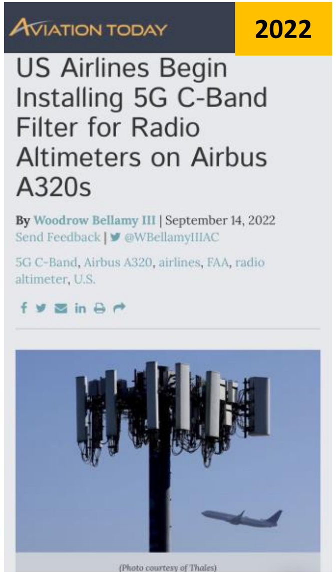


IEEE Spectrum Allocation

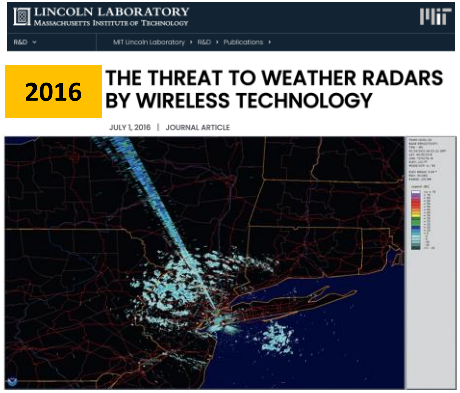
Modern radar/comms operate in an increasingly crowded RF spectrum

Radars need to use full bandwidth and undertake continuous transmissions

IEEE Radar band	VHF/UHF [30 MHz – 1 GHz]	L [1-2 GHz]	S [2-4 GHz]	C [4-8 GHz]	X [8-12 GHz]	Ku, K, Ka ,V, W [12-300 GHz]
Examples of radar usage	FOPEN	ARSR	ASR, NEXRAD	TDWR	CASA	Automotive radars, cloud radars
Co-existing comms	TV/broadcast/ 802.11ah/f	WiMAX, JTIDS	LTE	802.11a/ ac	LTE	802.11ad, mmwave comm


AVIATION TODAY
2022
US Airlines Begin Installing 5G C-Band Filter for Radio Altimeters on Airbus A320s
By Woodrow Bellamy III | September 14, 2022
Send Feedback | @WBellamyIIIAC
5G C-Band, Airbus A320, airlines, FAA, radio altimeter, U.S.
(Photo courtesy of Thales)


THE CONVERSATION
Academic rigor, journalistic flair
Radio interference from satellites is threatening astronomy – a proposed zone for testing new technologies could head off the problem
Published: March 3, 2023 8.24am EST
2023
Authors
Christopher Gordon De Pree
Deputy Electromagnetic Spectrum Manager, National Radio Astronomy Observatory
Christopher R. Anderson
Associate Professor of Electrical Engineering, United States Naval Academy
Mariya Zheleva
Assistant Professor of Computer Science, University at Albany, State University of New York


LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
2016
THE THREAT TO WEATHER RADARS BY WIRELESS TECHNOLOGY
JULY 1, 2016 | JOURNAL ARTICLE

DARPA

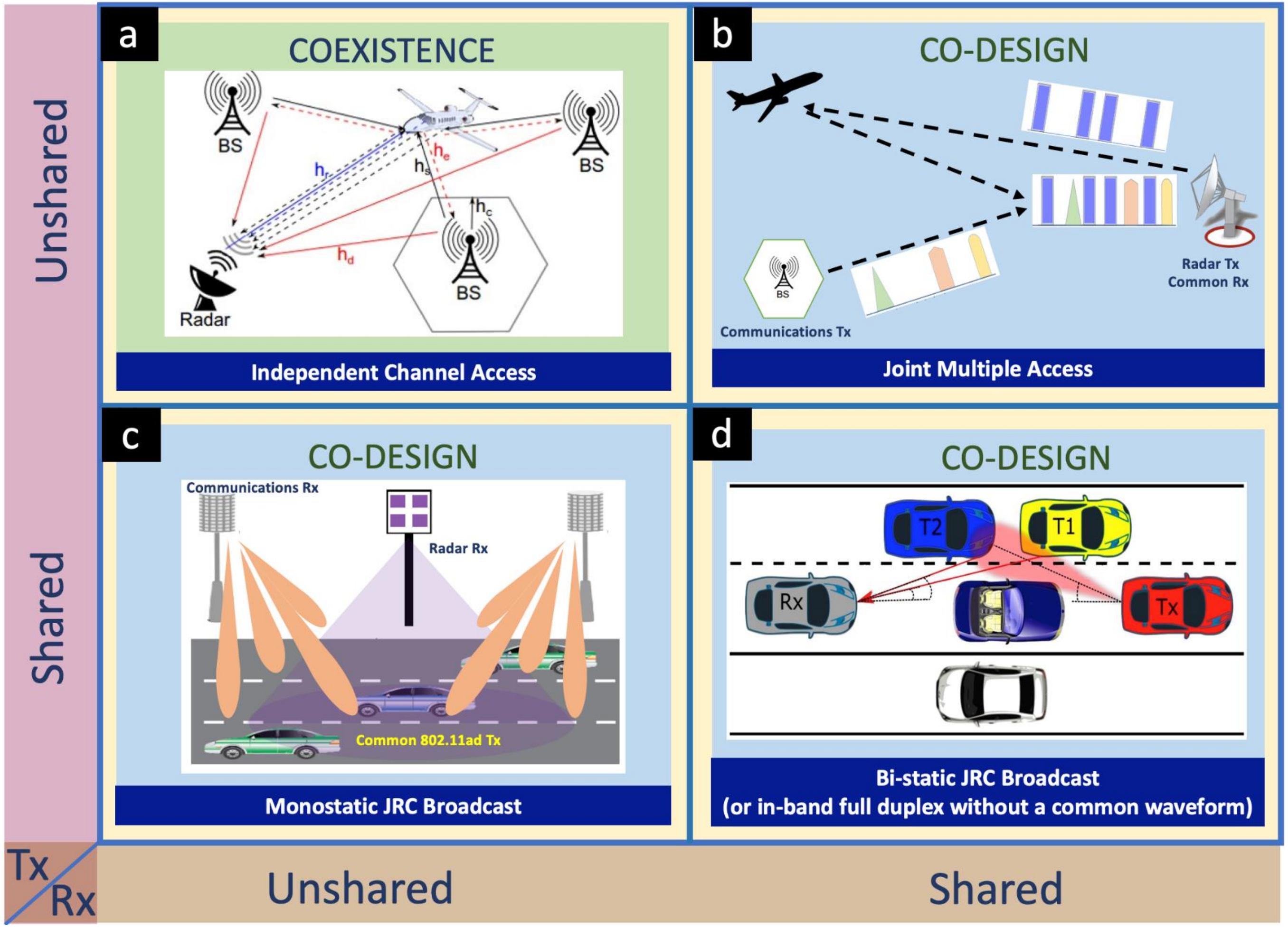
Shared Spectrum Access for Radar and Communications (SSPARC)

Platforms for Advanced Wireless Research

NRDZ
National Radio Dynamic Zone

RFDATA FACTORY

Integrated Sensing and Communications (ISAC) Topologies



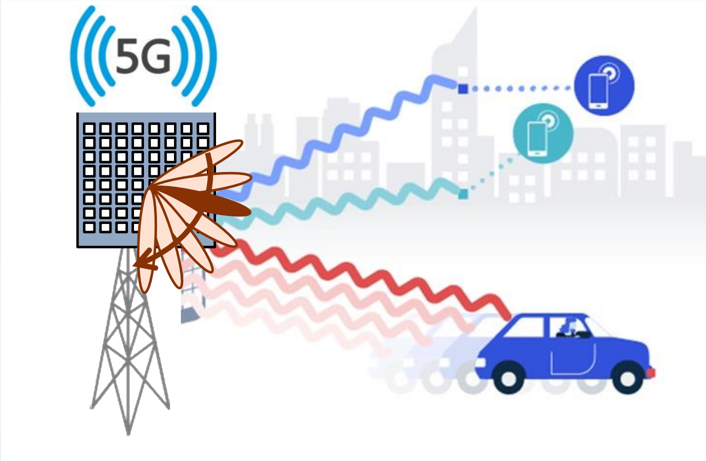
More ISAC Topologies

Channel Access	Hardware	Waveform
◆ Independent ◆ Coordinated ◆ Joint ◆ Shared	◆ Separate Tx & Rx ◆ Same Tx, Common Rx ◆ Common Tx, Same Rx ◆ Common Tx & Rx	◆ Separate ◆ Common ◆ Resource-shared
Location	**Performance/Functionality**	**Specialized**
◆ Colocated ◆ Bi-static ◆ Distributed ◆ Networked ◆ Heterogeneous	◆ Radar-centric ◆ Comms-centric ◆ Joint radar-comms ◆ Dual-Function Radar-Comms	◆ MRMC ◆ IBFD ISAC ◆ IRS-Aided ISAC ◆ mmWave, THz, VLC, quantum

Outline

- Motivation & Challenges
- **Spectral Co-Design**: Automotive JRC, Full-Duplex ISAC, Learning
- **Opportunistic ISAC**: Wi-Fi Protocol for Radar, Weather Sensing
- **Spectral Co-Existence**: Dual-Blind Deconvolution

Courtesy: Citadel (S01E06)

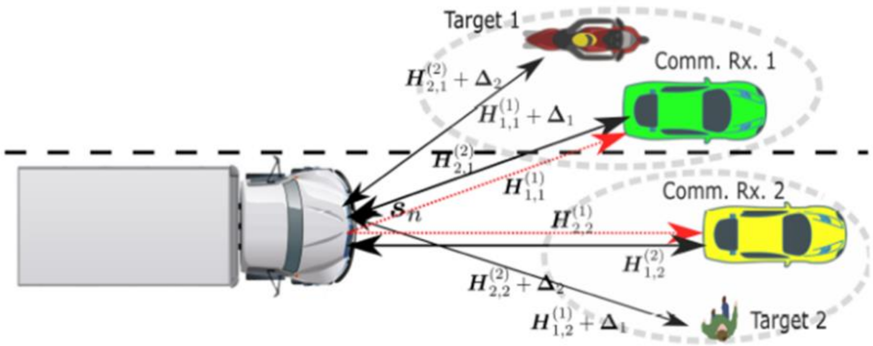


Spectral Co-Design

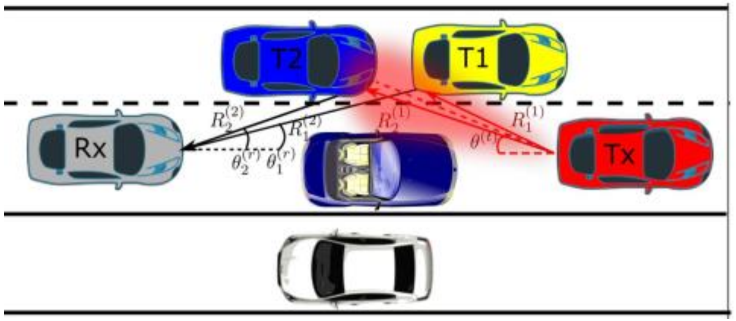
Automotive JRC

Monostatic and Bi-Static Systems

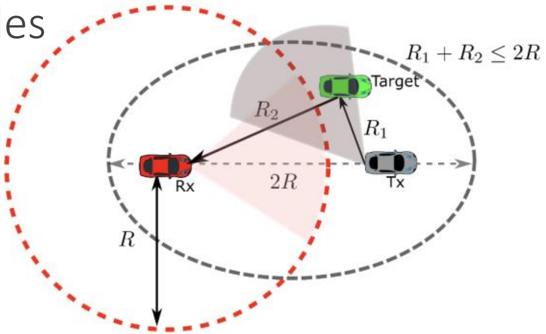
Monostatic



Bi-static

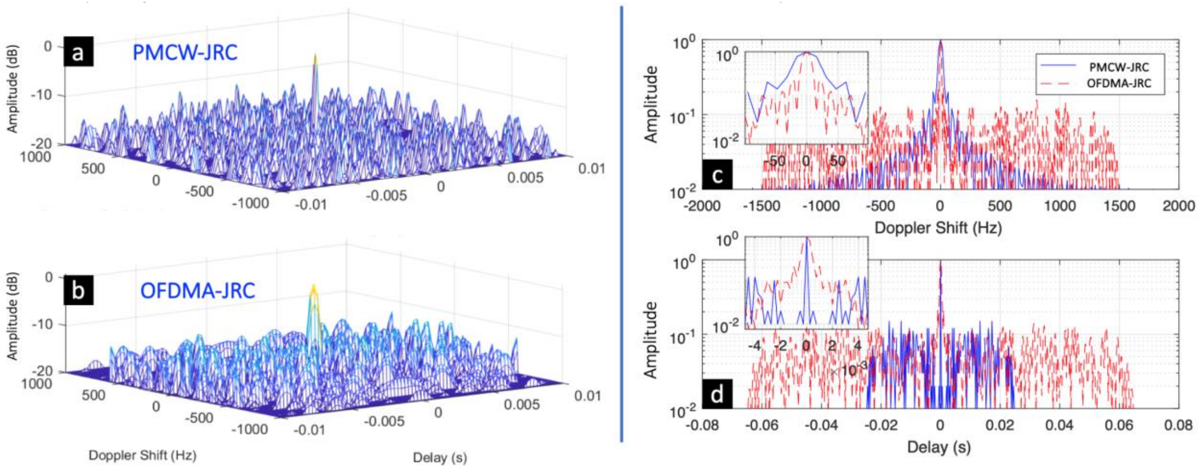


- Bi-static radar exploits bounced-off Tx signals from other vehicles
- Extends sensing area to NLOS w.r.t. Rx
- Communications is more susceptible to interference from surroundings than the direct path
- Bi-static system is more general

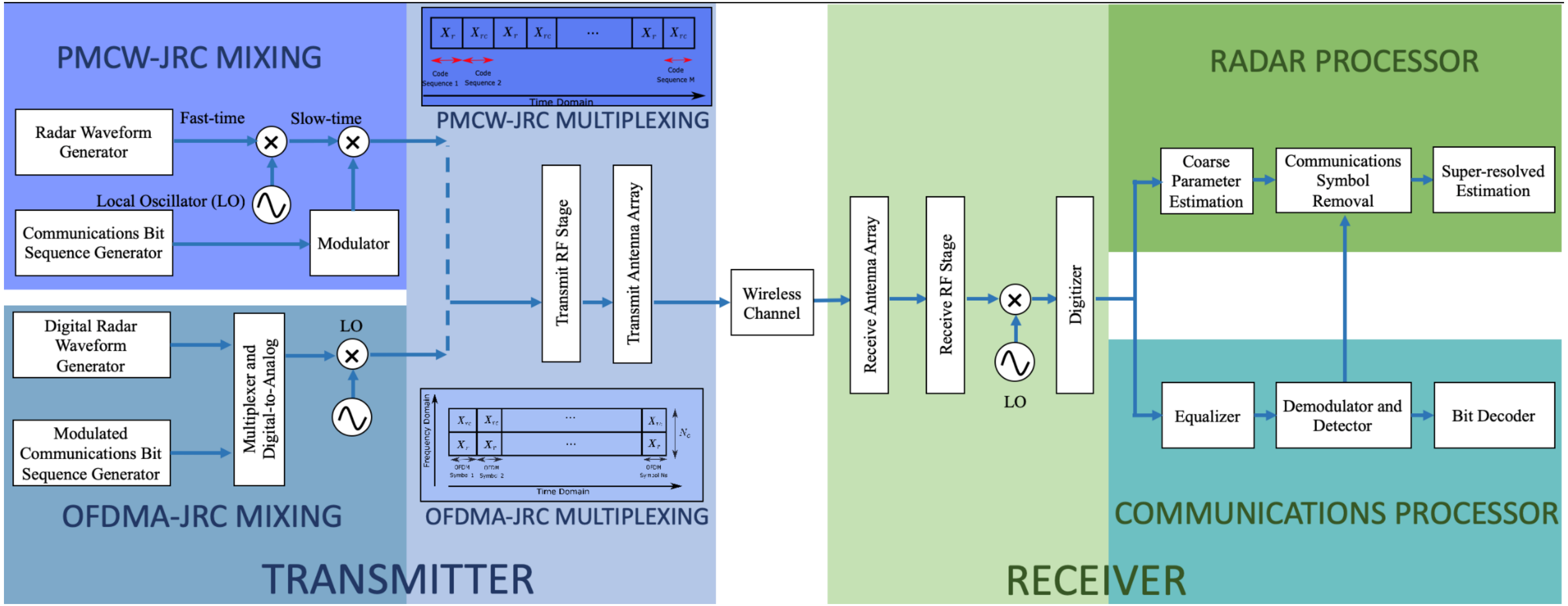


Two waveforms for mm-Wave JRC

- PMCW
  - Viable alternative to FMCW for high-res radars
  - No linear frequency ramp (and simpler on-chip implementations) for range estimation
  - Sharp, thumbtack ambiguity function; MIMO radar in code domain; embedded comms
- OFDMA
  - Differentiates users in both time and frequency (unlike OFDM in time-only)
  - Stable performance in multipath fading and relative simple synchronization
  - High dynamic range and efficient receiver processing based on FFT
- Question: H

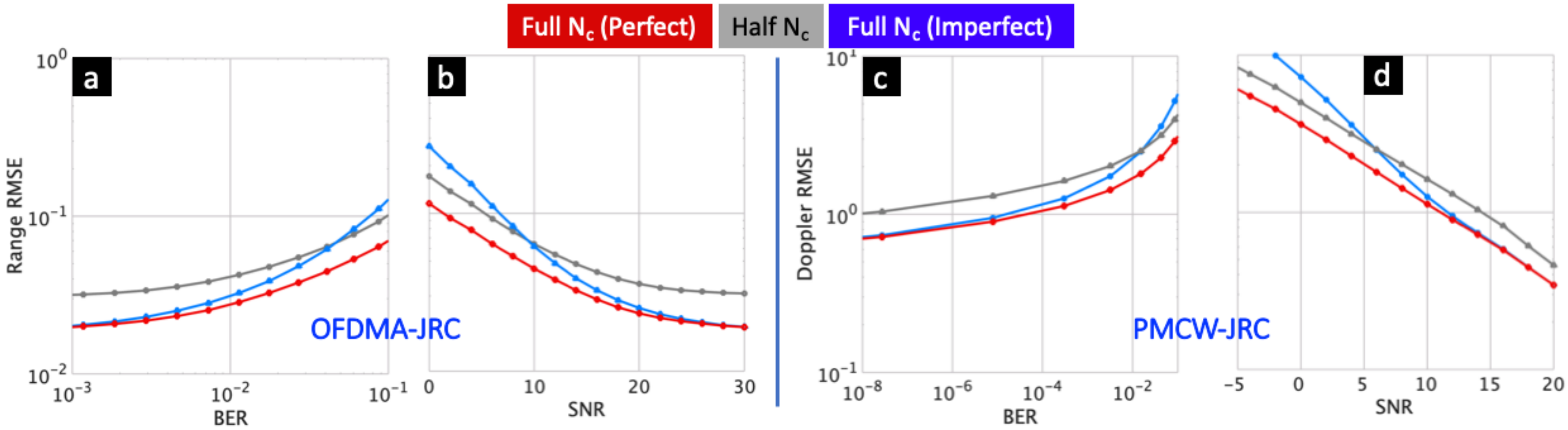


mm-Wave Tx-Rx Design

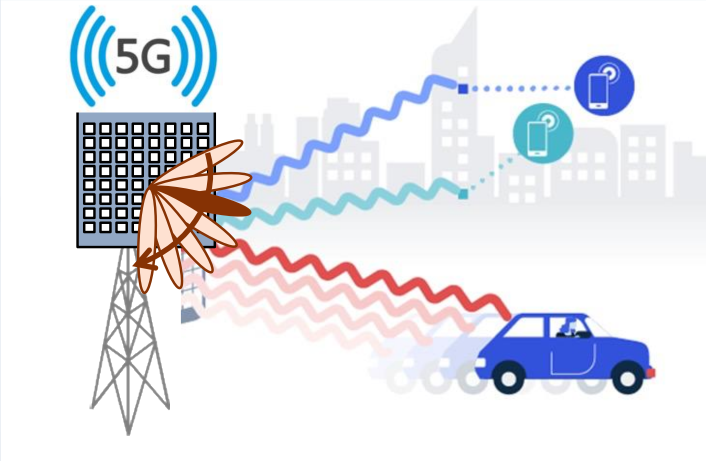


- Multiplexing strategy required to enhance waveform identifiability
- The receive processing consists of coarse and super-resolution steps
- JRC super-resolution algorithm has lower complexity than 2D-FFT and 2D-MUSIC

mm-Wave JRC Performance



- A comparison of estimation errors in the coupled parameter - range for OFDMA-JRC and Doppler for PMCW-JRC
- When SNR is above a threshold, re-estimating coupled parameter using all subcarriers after comm removal enhances the recovery
- At low SNR, radar-only frames/carriers are a more optimal choice

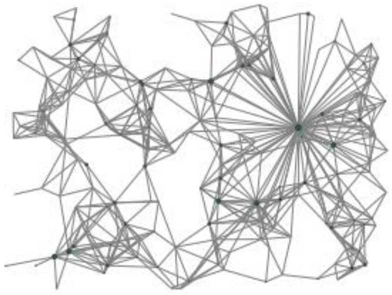


Spectral Co-Design

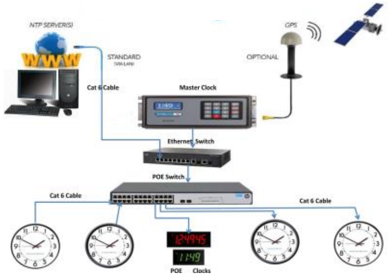
Distributed IBFD ISAC

Distributed ISAC Considerations

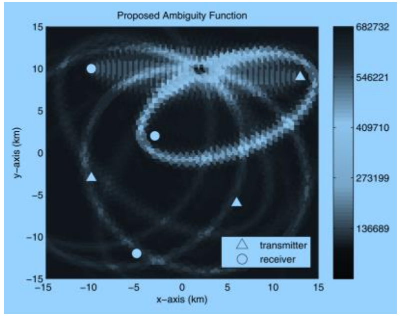
Challenge: Future networks will be more decentralized and edge-focused
Current research devoted to colocated/centralized ISAC



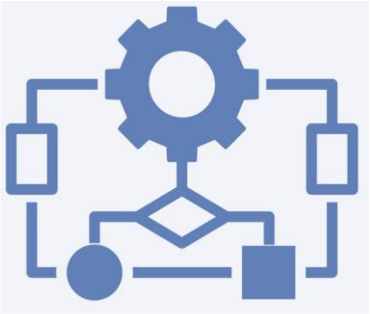
Complexity



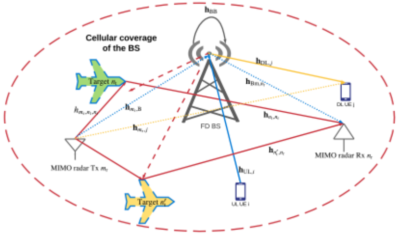
Synchronization



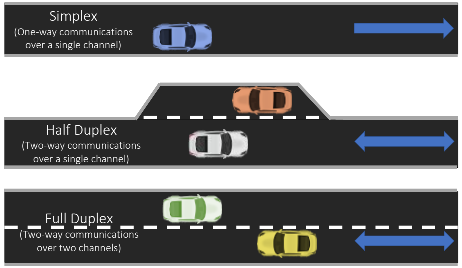
Statistical Design



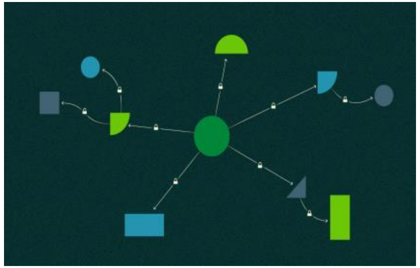
Speed



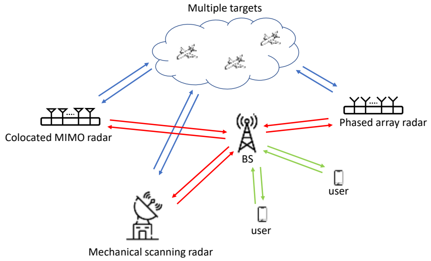
Data Association



Duplexing

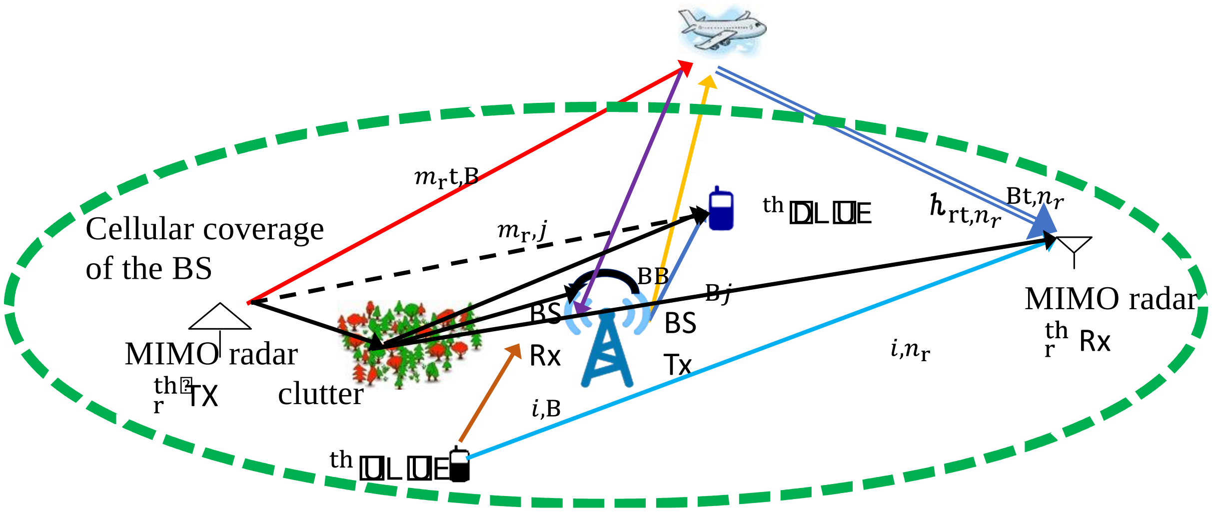


Fusion Center



Architectures

Statistical/Distributed Co-Design MRMC



Target RCS is not identical for all Tx-Rx pairs; modeled statistically

Radars work in cooperation with the downlink-reflected signal

IBFD MU-MIMO comms transmit while receiving target echoes

Determine a common metric for both radar and comms

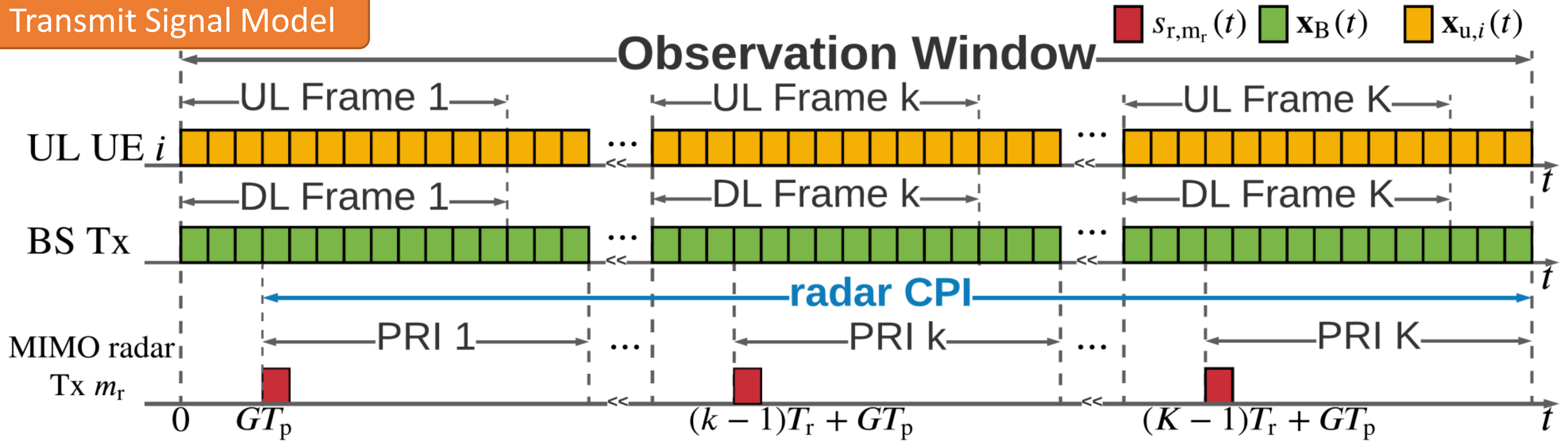
Compounded and weighted sum mutual information as metric

Practical constraints: power budget, QoS, and PAR

- J. Liu, K. V. Mishra and M. Saquib, "Co-Designing Statistical MIMO Radar and In-band Full-Duplex Multi-User MIMO Communications," arxiv preprint 2020.

Spectral Codesign System model

Transmit Signal Model



UL UE i: $\mathbf{x}_{u,i}(t) = \sum_{k=0}^{K-1} \sum_{l=0}^{N-1} \mathbf{P}_{u,i}[k] \; \mathbf{d}_{u,i}[k,l] \, p_T\big(t-(kN+l)T_p\big)$

Precoder of UL UE i

Data stream of UL UE i

Transmit pulse shape filter

Radar Tx m_r:

$\mathbf{s}_{m_r}(t) = \sum_{k=0}^{K-1} a_{m_r,k} \, \phi_{m_r}\big(t - kT_r - GT_p\big)$

Radar Tx m_r code in the k-th PRI

BS Tx: $\mathbf{x}_B(t) = \sum_{j=1}^{J} \sum_{k=0}^{K-1} \sum_{l=0}^{N-1} \mathbf{P}_{d,j}[k] \mathbf{d}_{d,j}[k,l] p_T\big(t-(kN+l)T_p\big)$

Precoder of DL UE j

Data stream for DL UE j

J. Liu, K. V. Mishra and M. Saquib, "Co-Designing Statistical MIMO Radar and In-band Full-Duplex Multi-User MIMO Communications," arxiv preprint 2020.

Spectral Codesign System model

Composite Receive Signal Model

Receive Signal at BS Rx to decode UL UE i:

$$\mathbf{y}_i^{\mathrm{u}}[k,l] = \mathbf{y}_{\mathrm{u},i}[k,l] + \mathbf{y}_{\mathrm{um},i}[k,l] + \mathbf{y}_{\mathrm{rB}}[k,l] + \mathbf{y}_{\mathrm{BB}}[k,l] + \mathbf{z}_{\mathrm{B}}[k,l]$$

Multiuser-interference

FD Self-interference

Receive Signal at DL UE j:

$$\mathbf{y}_j^{\mathrm{d}}[k,l] = \mathbf{y}_{\mathrm{d},j}[k,l] + \mathbf{y}_{\mathrm{dm},j}[k,l] + \mathbf{y}_{\mathrm{u},j}[k,l] + \mathbf{y}_{\mathrm{r},j}[k,l] + \mathbf{z}_{\mathrm{d},j}[k,l]$$

UL interfering signal

Receive Signal at radar Rx n_{r}:

$$\mathbf{y}_{n_r}^{\mathrm{r}}[k] = \mathbf{y}_{\mathrm{rt},n_r}[k] + \mathbf{y}_{\mathrm{Bt},n_r}[k] + \mathbf{y}_{\mathrm{Bm},n_r}[k] + \mathbf{y}_{\mathrm{u},n_r}[k] + \mathbf{y}_{\mathrm{c},n_r}[k] + \mathbf{z}_{\mathrm{r},nr}[k]$$

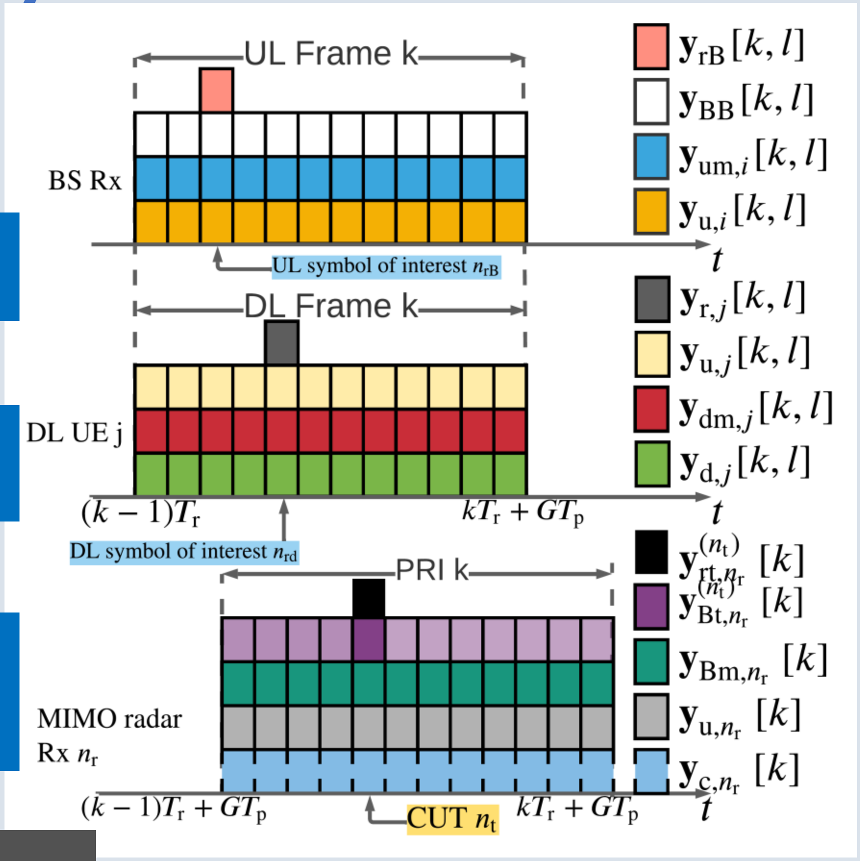
Target reflected DL signal

Multi-path propagated DL signal

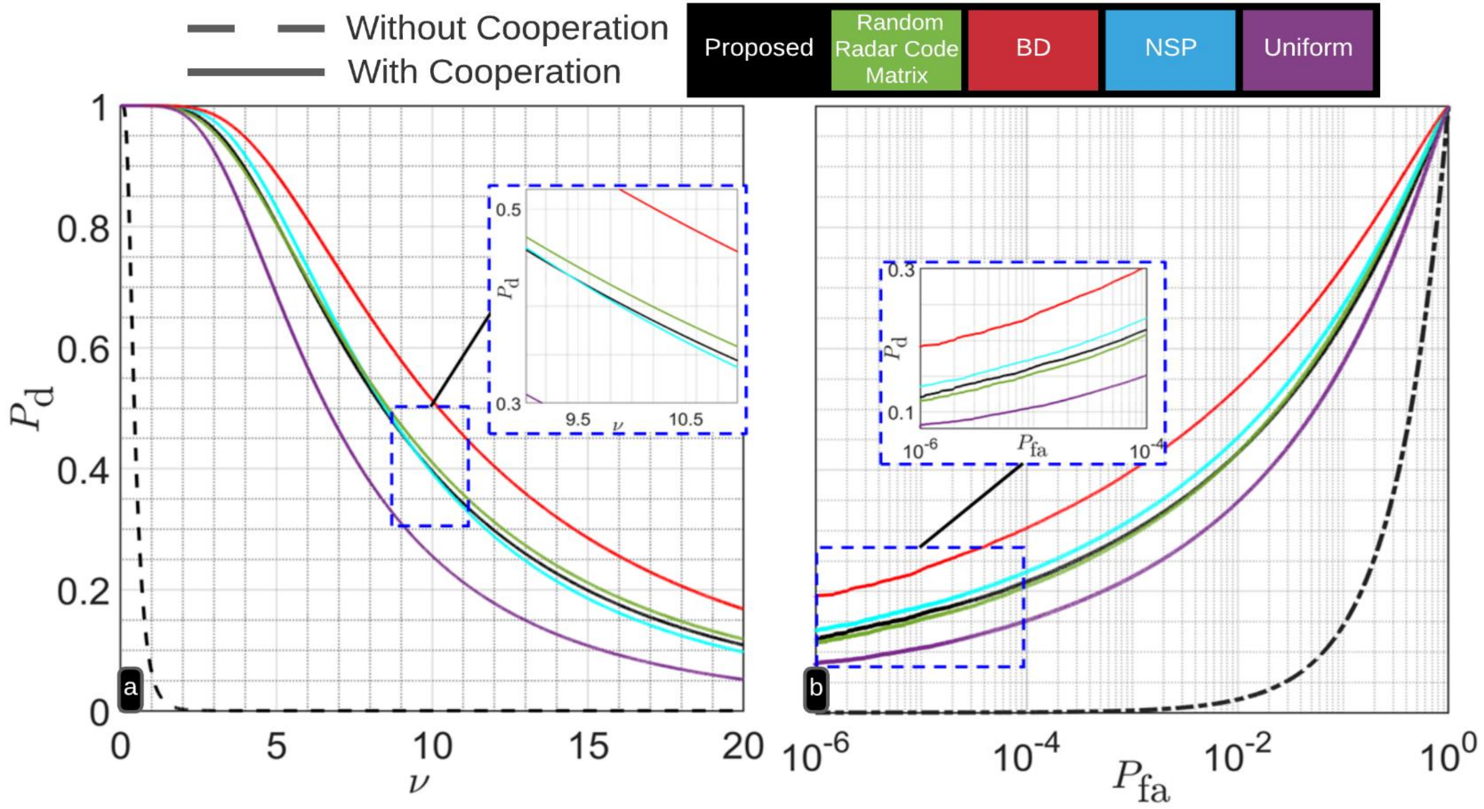
UL signal

Clutter signal

Complex Gaussian Noise vectors

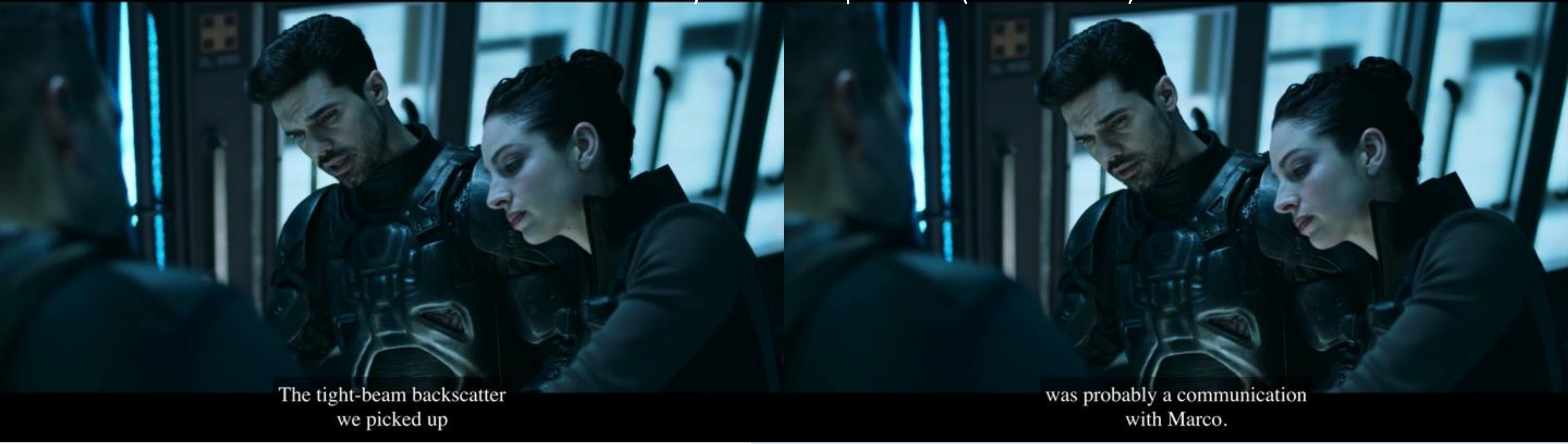


Numerical Experiments

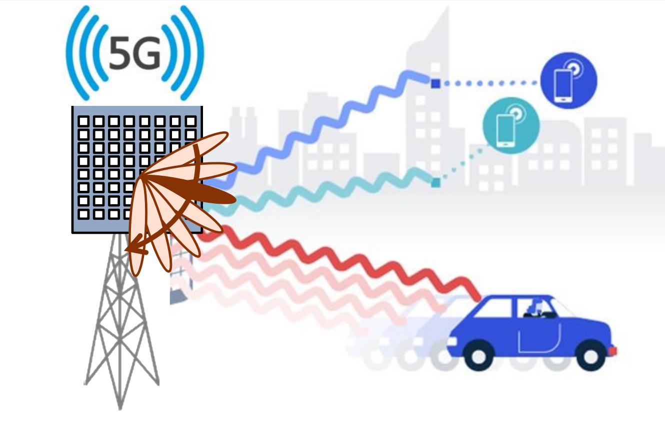


J. Liu, K. V. Mishra and M. Saquib, "Co-Designing Statistical MIMO Radar and In-band Full-Duplex Multi-User MIMO Communications," arxiv preprint 2020.

Courtesy: The Expanse (Season 5)



Spectral Co-Design
Learning for JRC Hybrid Beamforming



When ML makes sense in ISAC?

Model/Algorithm Deficit

- Conventional engineering approach is not applicable because models stemming from physics/mathematics/algorithms cannot be rigorously specified
- Sufficiently large training data sets exhibiting all the variation in the observed data sets available or can be created (e.g., using GANs)
- Labeling of training data can be done with a reasonable effort

Tasks

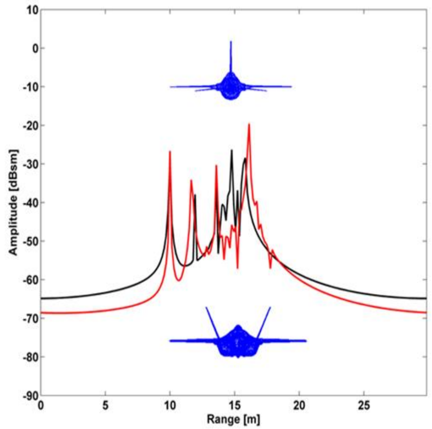
- Need for Narrow AI with super-human performance, no need for broader intelligence
- The task does not need explicit reasoning based on broader background knowledge.
- No requirement of rigorous quantitative performance guarantees/explicit explanations for how the result was found

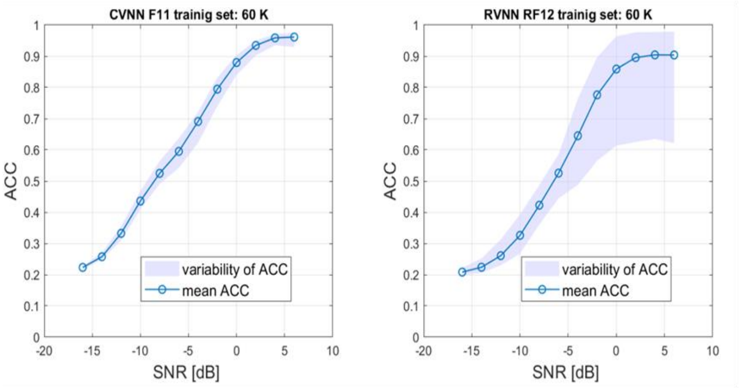
Results

- Numerical simulations suffice instead of analytical optimality results
- Learned phenomenon remains stationary to acquire large amount of training data

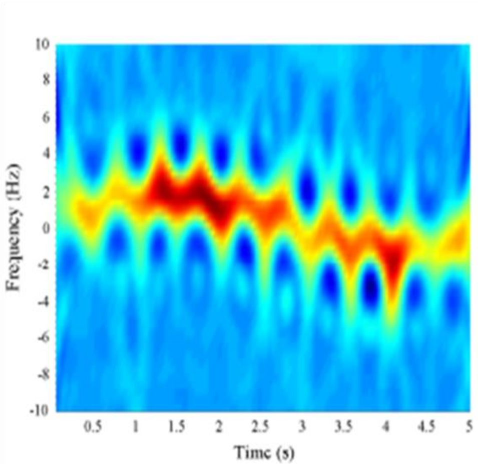
Deep learning examples in radar sensing

- Target classification using deep learning and HRRPs
- Waveform classification using complex-valued and real-valued NNs
- CNNs give better and more predictable performance with less training data and smaller NN



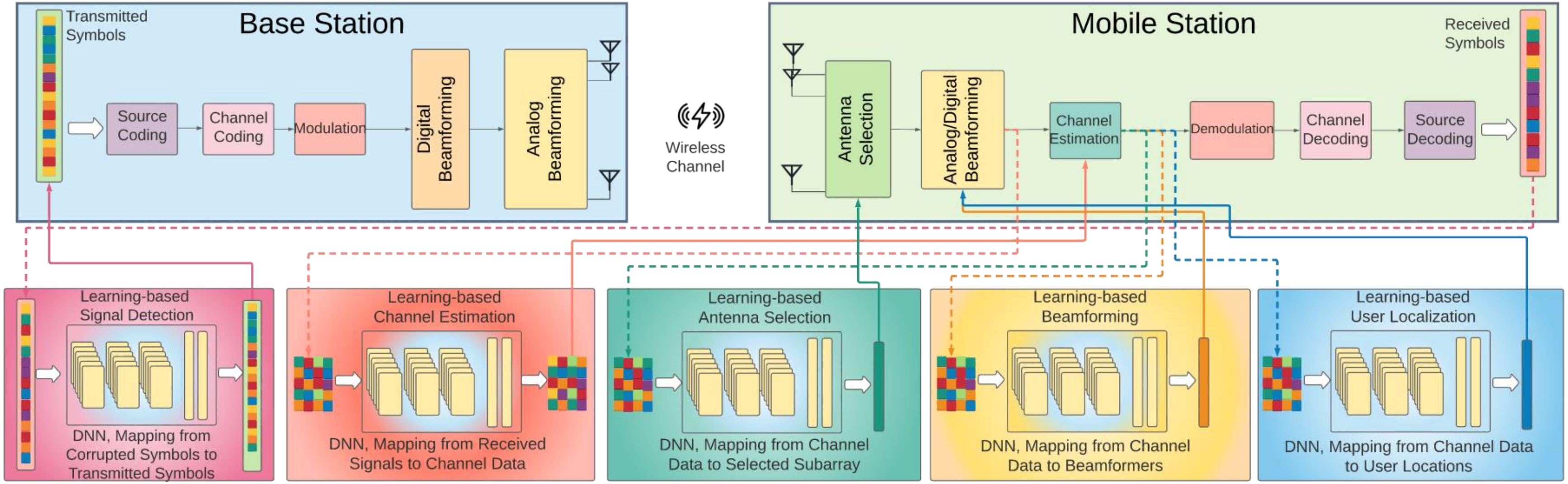


- Analysis of micro-doppler signatures



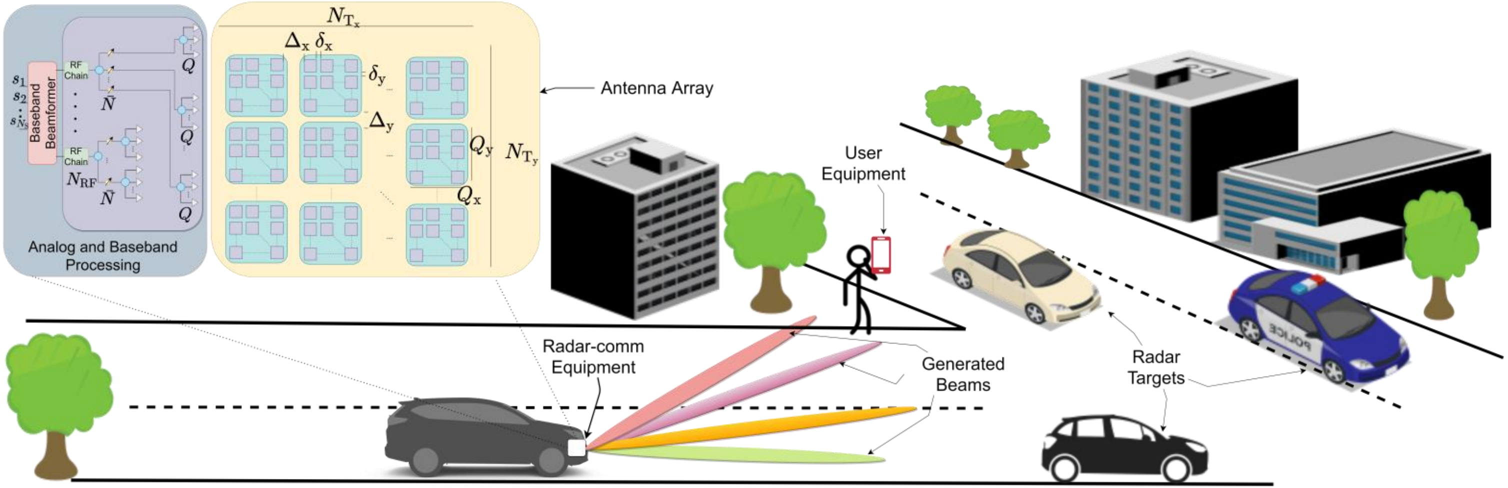
Deep Learning Applications in Comms Physical Layer

DL can be used for various PHY applications.



Elbir, Ahmet M. and Kumar Vijay Mishra. "Cognitive Learning-Aided Multi-Antenna Communications.'', IEEE Wireless Communications, in press.

THz ISAC Hybrid Beamforming via Deep Learning



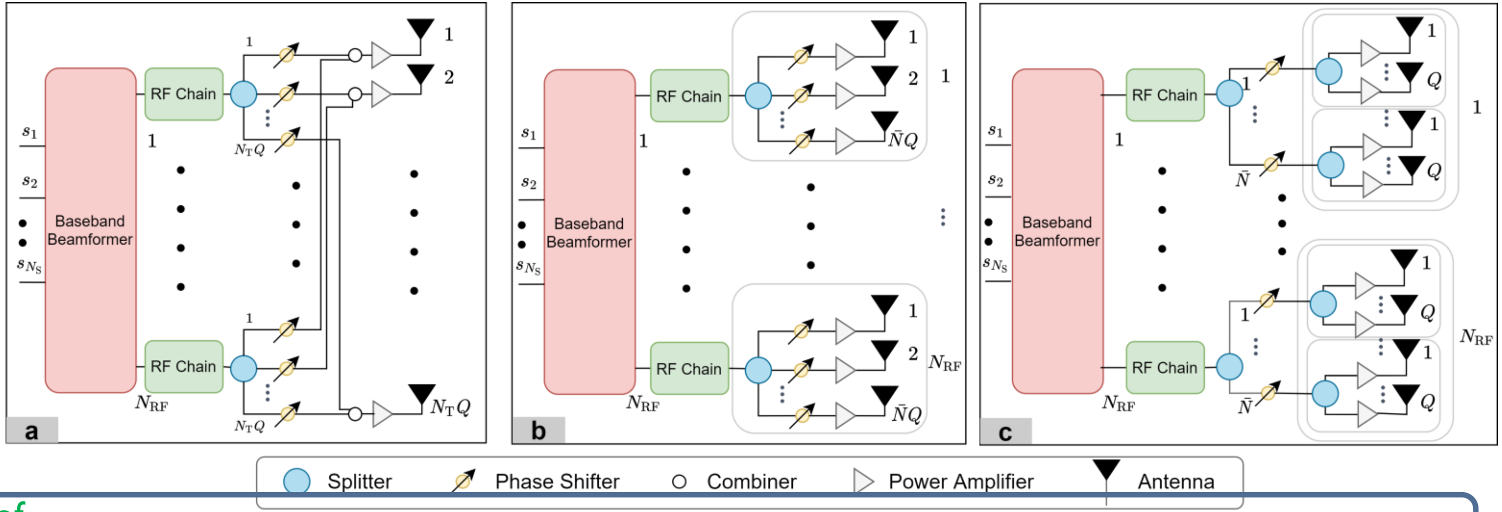
Major Challanges in THz Hybrid Beamforming :

- High path loss: LoS-dominant with multiple NLoS channel
- Ultra-massive number of antennas: Group-of-subarrays (GoSA)
- Complexity: Deep-learning-based solutions

Elbir, Ahmet M., et al. "Terahertz-Band Joint Ultra-Massive MIMO Radar-Communications: Model-Based and Model-Free Hybrid Beamforming.'', IEEE Journal of Selected Topics in Signal Processing, vol. 15, no. 6, pp. 1468-1483, Nov. 2021

THz ISAC Hybrid Beamforming via Deep Learning

Fully-connected | Array-of-subarrays (AoSA) | Group-of-subarrays (GoSA)



Number of phase shifters: $N_T Q N_{RF}$ | $\bar{N}Q \quad (\bar{N} = \frac{N_T}{N_{RF}})$ | N_T

Major Challanges in THz Hybrid Beamforming :

- High path loss: LoS-dominant with multiple NLoS channel
- **Ultra-massive number of antennas: Group-of-subarrays (GoSA)**
- Complexity: Deep-learning-based solutions

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THz ISAC Hybrid Beamforming via Deep Learning

Communications

$$\min_{\mathbf{F}_{\mathrm{RF}},\{\mathbf{F}_{\mathrm{BB}}[m]\}_{m\in\mathcal{M}}} \frac{1}{M}\sum_{m\in\mathcal{M}} \|\mathbf{F}_{\mathrm{RF}}\mathbf{F}_{\mathrm{BB}}[m] - \mathbf{F}_{\mathrm{C}}[m]\|_{\mathcal{F}}$$

$$\text{s.t.} \sum_{m\in\mathcal{M}} \|\mathbf{F}_{\mathrm{RF}}\mathbf{F}_{\mathrm{BB}}[m]\|_{\mathcal{F}} = MN_{\mathrm{S}},$$

$$|[\mathbf{F}_{\mathrm{RF}}]_{i,j}| = \frac{1}{\sqrt{N_{\mathrm{T}}}}, \quad \forall i,j.$$

Radar

$$\min_{\mathbf{F}_{\mathrm{RF}},\{\mathbf{F}_{\mathrm{BB}}[m],\mathbf{P}[m]\}_{m\in\mathcal{M}}} \frac{1}{M}\sum_{m\in\mathcal{M}} \|\mathbf{F}_{\mathrm{RF}}\mathbf{F}_{\mathrm{BB}}[m] - \mathbf{F}_{\mathrm{R}}\mathbf{P}[m]\|_{\mathcal{F}}$$

$$\text{s.t.} \sum_{m\in\mathcal{M}} \|\mathbf{F}_{\mathrm{RF}}\mathbf{F}_{\mathrm{BB}}[m]\|_{\mathcal{F}} = MN_{\mathrm{S}},$$

$$|[\mathbf{F}_{\mathrm{RF}}]_{i,j}| = \frac{1}{\sqrt{N_{\mathrm{T}}}}, \quad \forall i,j,$$

$$\mathbf{P}[m]\mathbf{P}^{\mathsf{H}}[m] = \mathbf{I}_{N_{\mathrm{S}}}$$

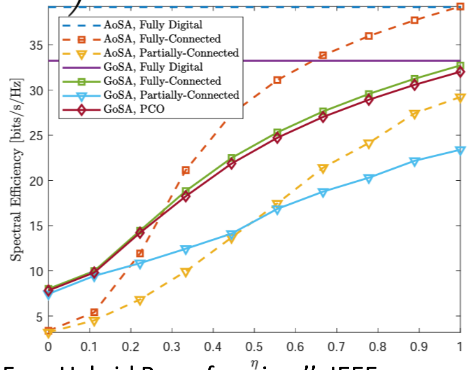
JRC Hybrid Beamforming Design

$$\min_{\mathbf{F}_{\mathrm{RF}},\{\mathbf{F}_{\mathrm{BB}}[m],\mathbf{P}[m]\}_{m\in\mathcal{M}}} \frac{1}{M}\sum_{m\in\mathcal{M}} \Big(\eta\|\mathbf{F}_{\mathrm{RF}}\mathbf{F}_{\mathrm{BB}}[m] - \mathbf{F}_{\mathrm{C}}[m]\|_{\mathcal{F}} + \bar{\eta}\|\mathbf{F}_{\mathrm{RF}}\mathbf{F}_{\mathrm{BB}}[m] - \mathbf{F}_{\mathrm{R}}\mathbf{P}[m]\|_{\mathcal{F}}\Big)$$

$$\text{s.t.} \sum_{m\in\mathcal{M}} \|\mathbf{F}_{\mathrm{RF}}\mathbf{F}_{\mathrm{BB}}[m]\|_{\mathcal{F}} = MN_{\mathrm{S}},$$

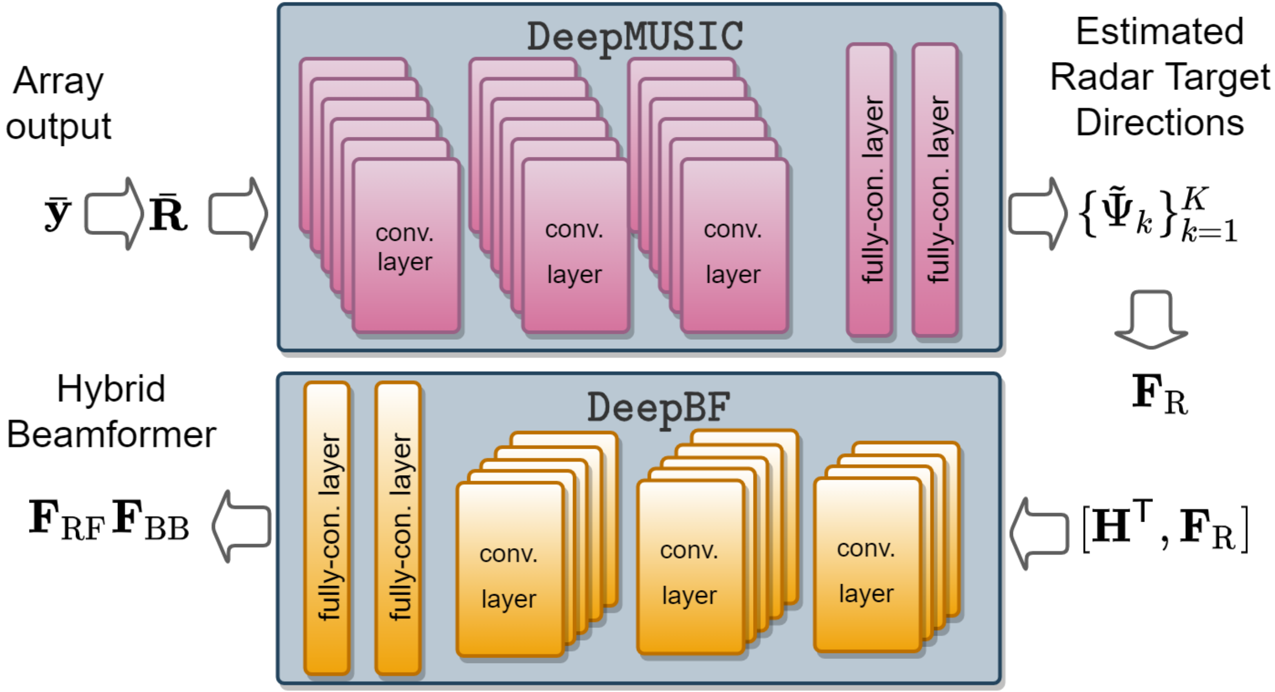
$$|[\mathbf{F}_{\mathrm{RF}}]_{i,j}| = \frac{1}{\sqrt{N_{\mathrm{T}}}}, \quad \forall i,j \in \mathcal{S}, \; |[\mathbf{F}_{\mathrm{RF}}]_{i,j}| = 0, \quad \forall i,j \in \bar{\mathcal{S}},$$

$$\mathbf{P}[m]\mathbf{P}^{\mathsf{H}}[m] = \mathbf{I}_{N_{\mathrm{S}}}$$



Elbir, Ahmet M., et al. "Terahertz-Band Joint Ultra-Massive MIMO Radar-Communications: Model-Based and Model-Free Hybrid Beamforming.'', IEEE Journal of Selected Topics in Signal Processing, vol. 15, no. 6, pp. 1468-1483, Nov. 2021

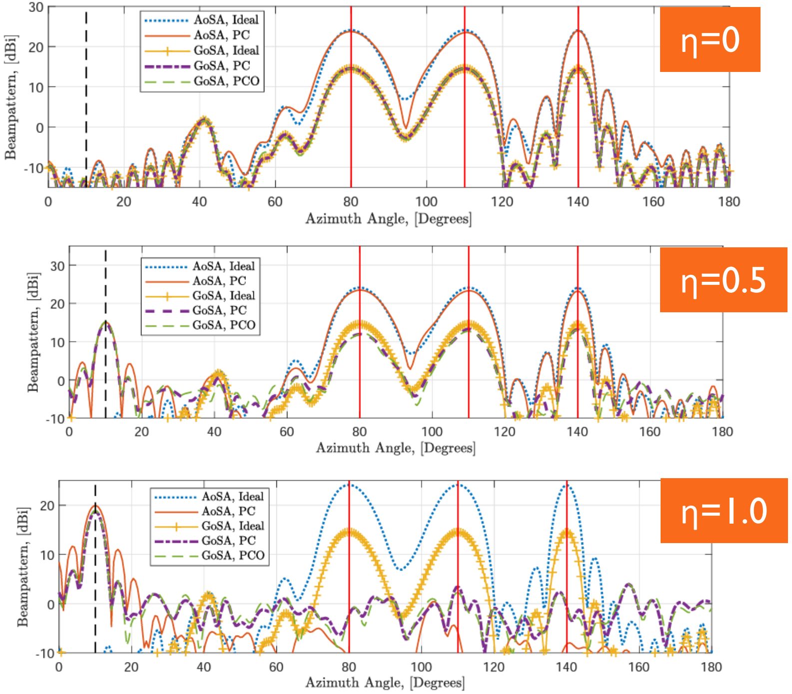
THz ISAC Hybrid Beamforming via Deep Learning



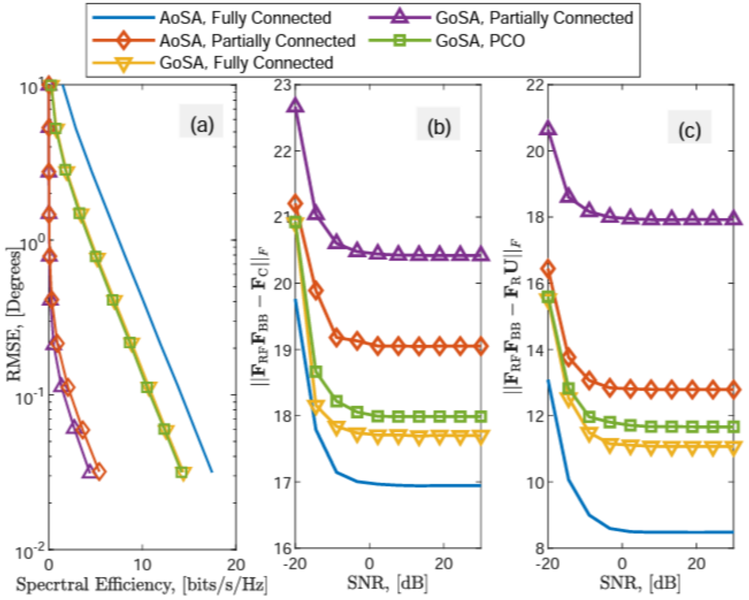
Elbir, Ahmet M., et al. "Terahertz-Band Joint Ultra-Massive MIMO Radar-Communications: Model-Based and Model-Free Hybrid Beamforming.'', IEEE Journal of Selected Topics in Signal Processing, vol. 15, no. 6, pp. 1468-1483, Nov. 2021

THz ISAC Hybrid Beamforming via Deep Learning

Radar-only



Comms-only



Varying SNR

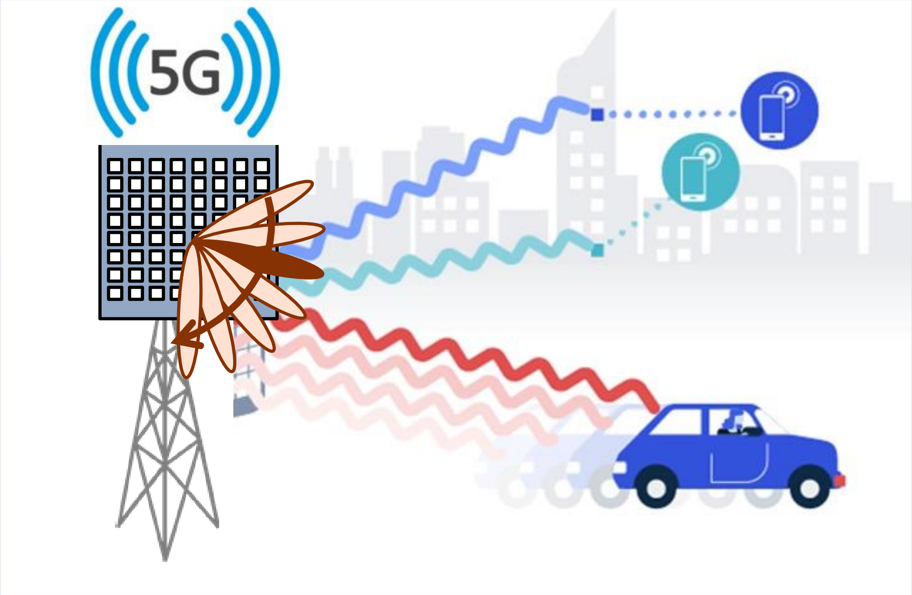
Cost fn of comms BF

Cost fn of radar BF

Elbir, Ahmet M., et al. "Terahertz-Band Joint Ultra-Massive MIMO Radar-Communications: Model-Based and Model-Free Hybrid Beamforming.'', IEEE Journal of Selected Topics in Signal Processing, vol. 15, no. 6, pp. 1468-1483, Nov. 2021

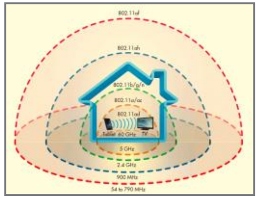
Opportunistic ISAC

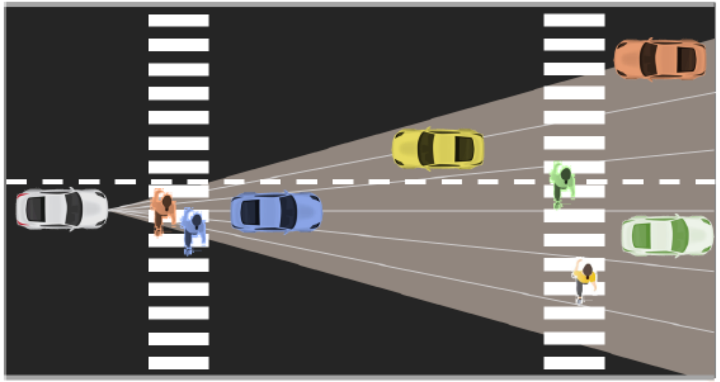
Using Wi-Fi Protocol for Radar



802-11ad-Based Joint Radar-Comms

- IEEE 802.11ad Wi-Fi standard enables high-throughput (7 Gbps) at 60 GHz
  - Very high rate (~GHz) ADCs → More power, space and cost
  - Can be exploited for a concurrent radar application
- Applications: parking assistance, lane change assistance, object detection

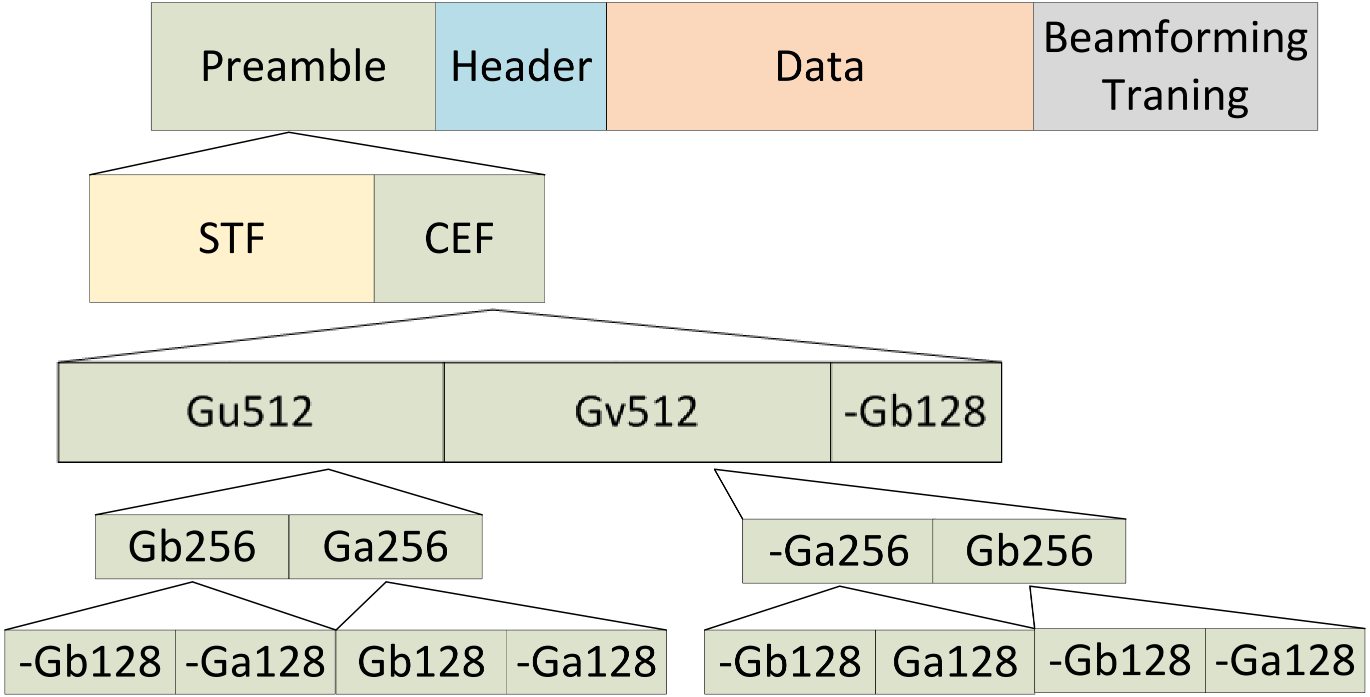




Parameters	Current literature	Proposed radar
Range	Long range (200m)	Short range (40m)
Target model	Simple point targets	Extended targets
Type of target	Static targets	Dynamic targets
Golay sequence	Standard	Modified / Doppler resilient

IEEE 802.11ad Frame Structure

- Single Carrier PHYsical layer (SCPHY) encapsulates Golay sequences

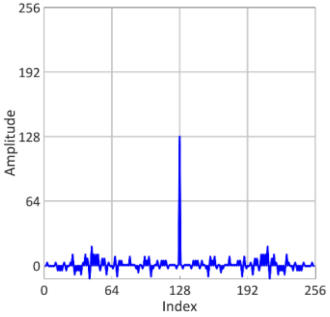


- 802.11ad Golay sequences: Two 256-length or four 128-length pairs

Golay Complementary Sequences (Golay Pairs)

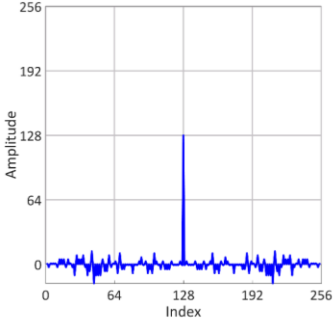
- Time-domain Property: Zero sidelobes

$Ga_N[n] * Ga_N[-n]$



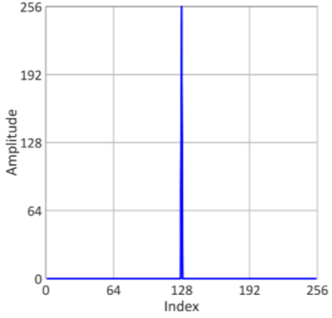
$+$

$Gb_N[n] * Gb_N[-n]$



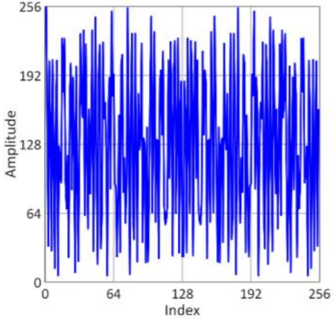
$=$

$2N\delta[n]$



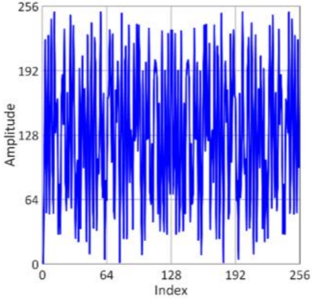
- Frequency-domain Property: Constant spectrum

$|Fa_N[k]|^2$



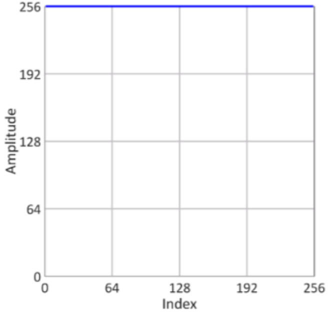
$+$

$|Fb_N[k]|^2$



$=$

$2N$

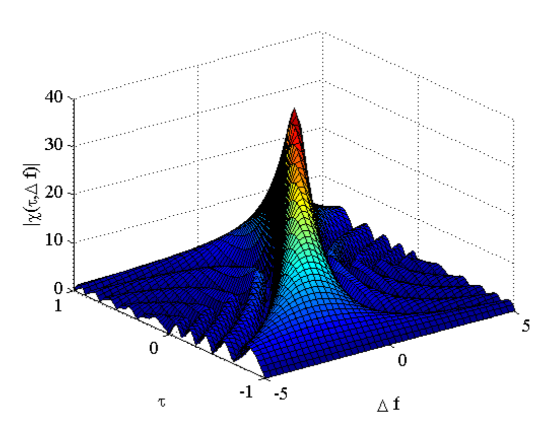


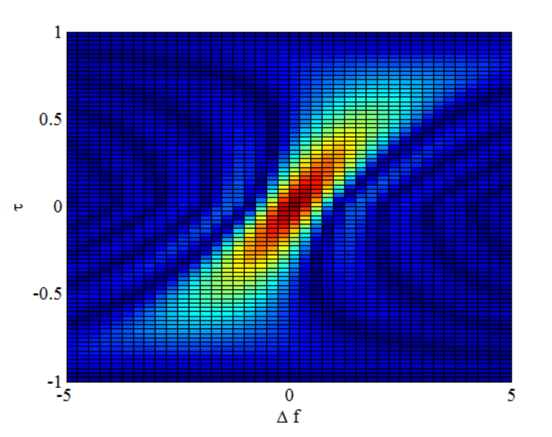
Good Autocorrelation, but Doppler Resilience?

Good Autocorrelation → Low Range Sidelobes → Enhanced Static Target Discrimination → Golay sequences attractive → 802.11ad good for JRC?

Dynamic Scenarios → Doppler, Delay → Good ACF in both domains

Ambiguity Function : $AF(t,\omega) = \int x(\tau)x^*(\tau - t)e^{j\omega\tau}d\tau$





Doppler-Resilient FMCW Waveform

Is 802.11ad Preamble Doppler-Resilient ?

$$G_{a,N}[n] * G_{a,N}[-n] + G_{b,N}[n] * G_{b,N}[-n] = 2N\delta[n].$$

$$(G_{a,N}[n] * G_{a,N}[-n]) + (G_{b,N}[n] * G_{b,N}[-n])\, e^{-j\theta} \neq 2N\delta[n]$$

Modification to 802.11ad

RQ1 — Doppler Resilient Preamble

RQ2 — Identical field width

RQ3 — Receiver operation unchanged

Prouhet-Thou-Morse (PTM) (Pezeshki et al., 2008) sequence to make the protocol Doppler-resilient

Prouhet-Thue-Morse (PTM) Sequence

$$q_p = \begin{cases} 0, & \text{if } p = 0 \\ q_{\frac{p}{2}}, & \text{if } (p \text{ modulo } 2) = 0 \\ \overline{q_{\frac{p-1}{2}}}, & \text{if } (p \text{ modulo } 2) = 1, \end{cases}$$

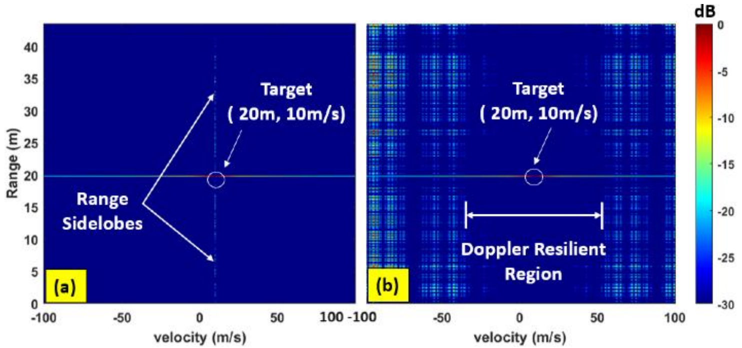
Modified Golay sequence

$$\text{if } q_p = 0, \{G_{a,N}[n], G_{b,N}[n]\}$$
$$\text{if } q_p = 1, \{-G_{b,N}[-n], G_{a,N}[-n]\}$$

Example

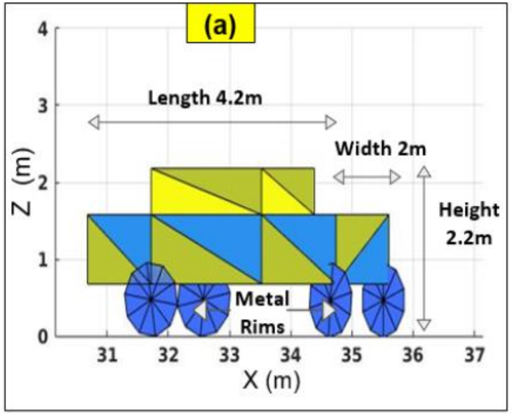
PTM Sequence: $[01] : G_{a,N}[n], G_{b,N}[n], -G_{b,N}[-n], G_{a,N}[-n]$:

$$\sum_{p=0}^{3} e^{-jp\theta}(G_{p,N}[n] * G_{p,N}[-n]) \approx 1((G_{1,N}[n] * G_{1,N}[-n]) + (G_{3,N}[n] * G_{3,N}[-n]))$$
$$+2((G_{2,N}[n] * G_{2,N}[-n]) + (G_{3,N}[n] * G_{3,N}[-n]))$$
$$= (2N + 2(2N))\delta[n] = 6N\delta[n].$$

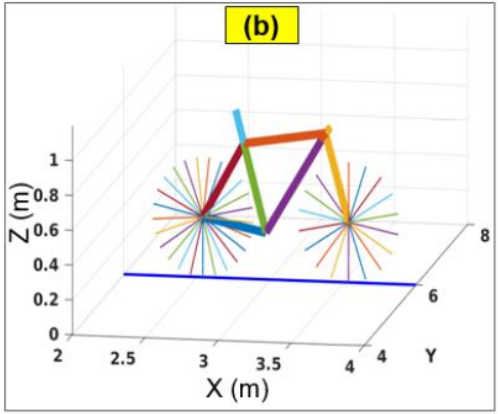


A. Pezeshki, A. R. Calderbank, W. Moran, and S. D. Howard, "Doppler resilient Golay complementary waveforms," IEEE Transactions on Information Theory, 54(9), 4254-4266, 2008.

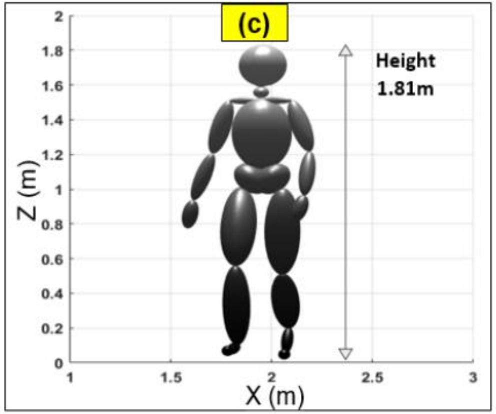
Extended Target Modeling (via PyBullet)



CAR



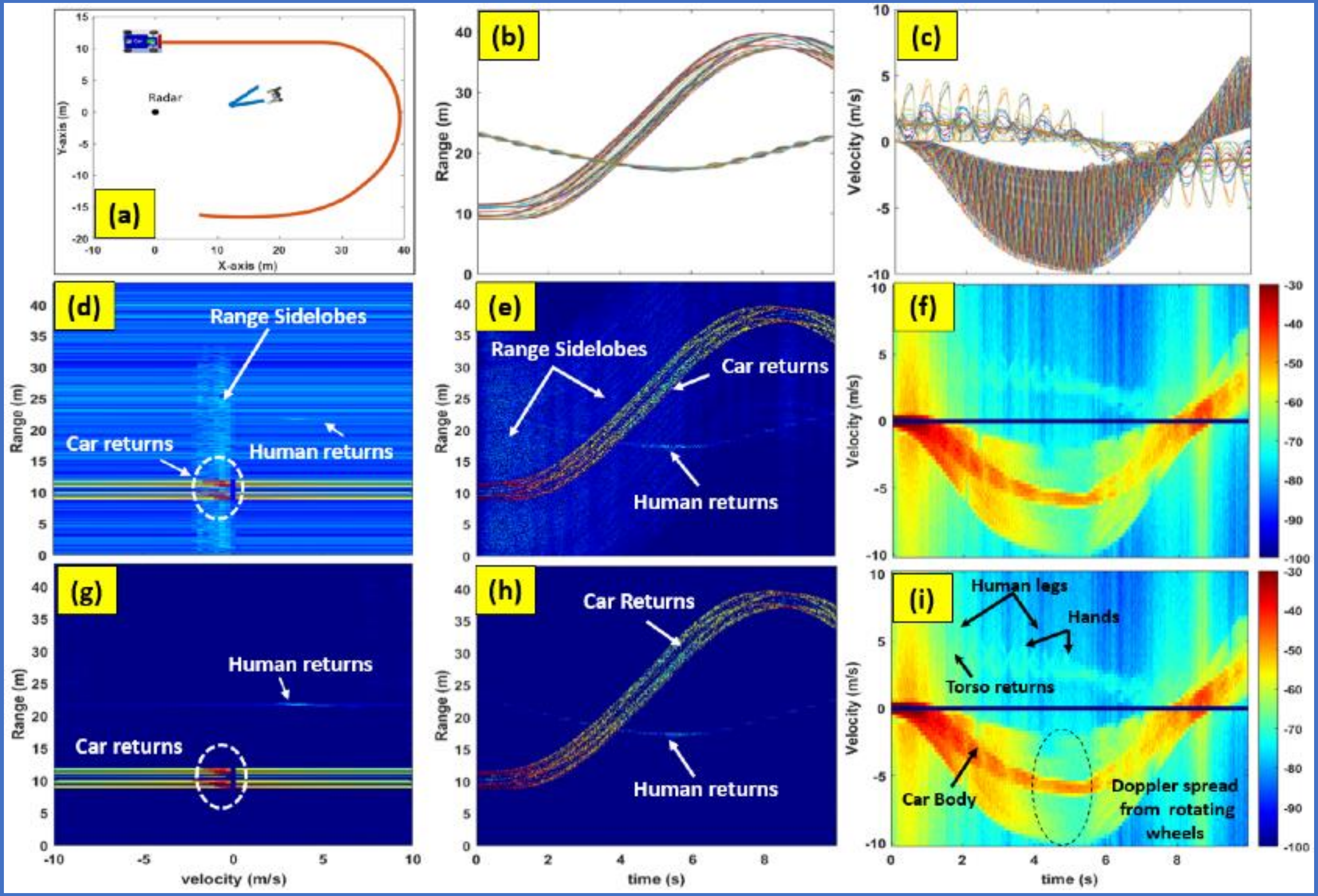
BICYCLE



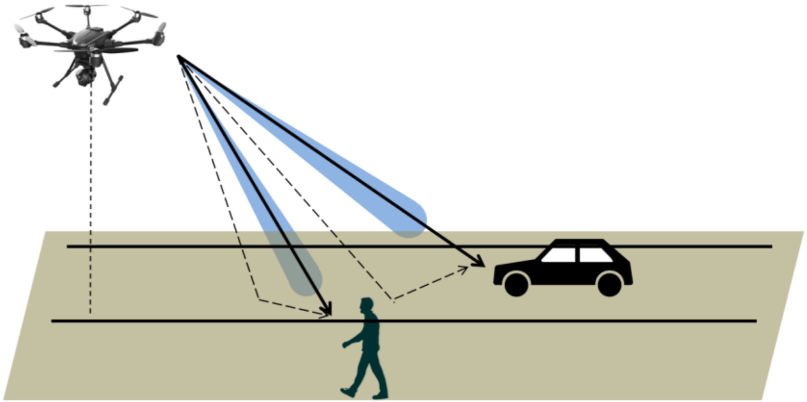
PEDESTRIAN

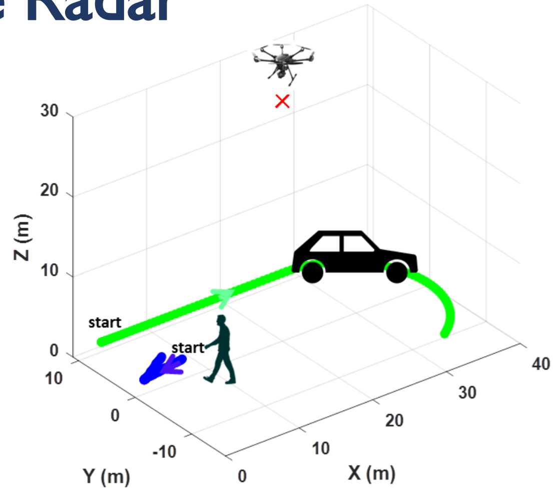
G. Duggal, S. Vishwakarma, K. V. Mishra and S. S. Ram, "Doppler-Resilient 802.11ad-Based Ultrashort Range Automotive Joint Radar-Communications System," IEEE Transactions on Aerospace and Electronic Systems, vol. 56, no. 5, pp. 4035-4048, 2020.

Extended Target Modeling Results – Multiple Targets

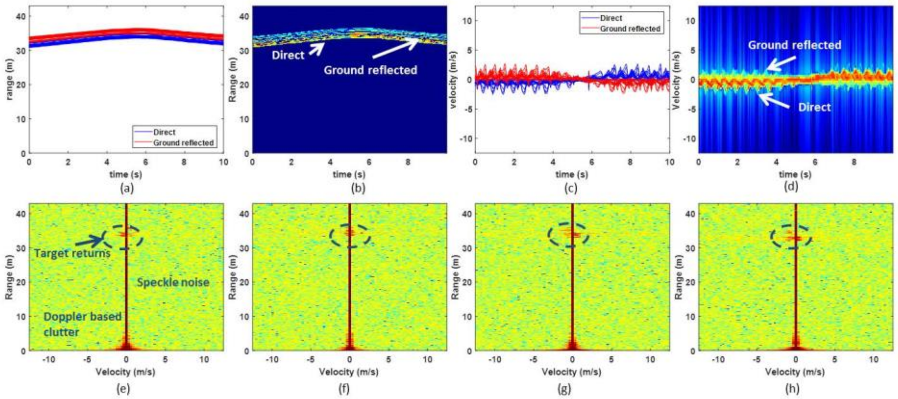


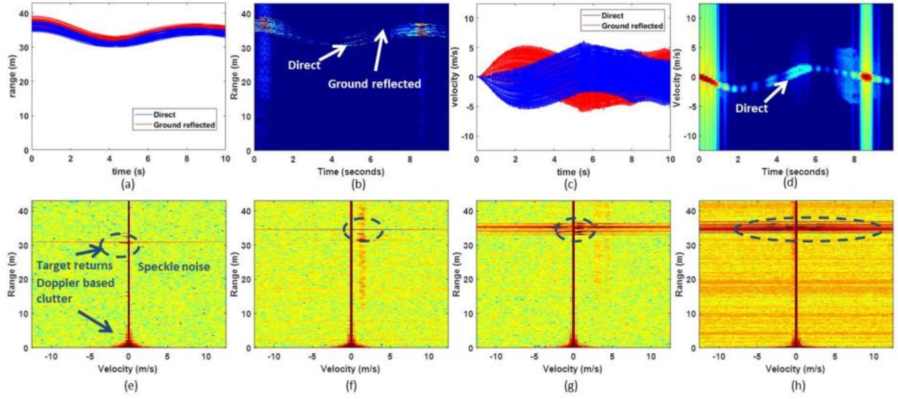
802.11ad-Based UAV-Borne Radar





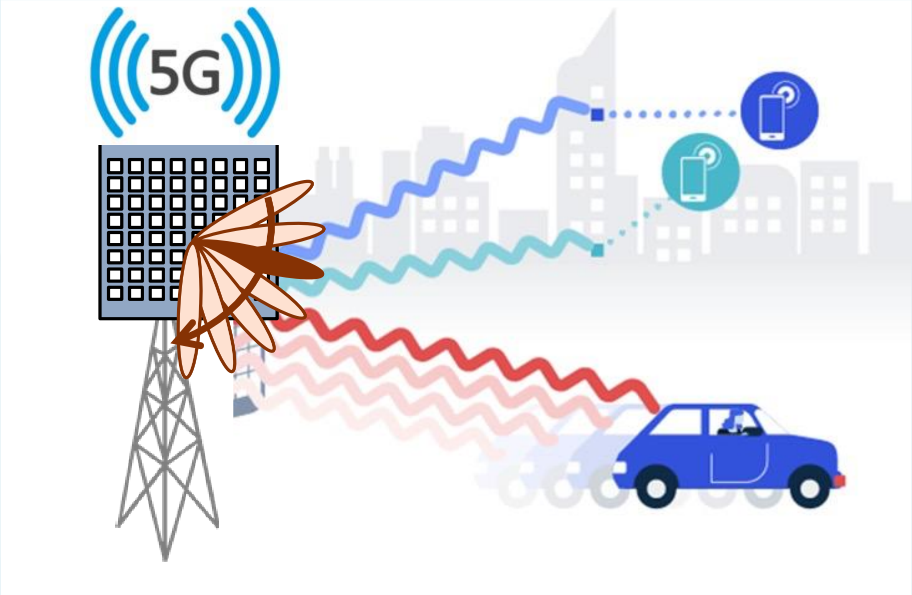
Surface clutter models and PyBullet modeling used to obtain the signatures





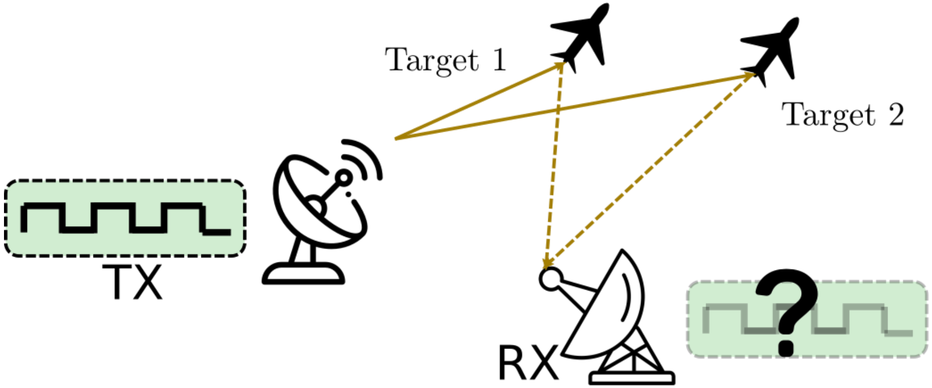
S. S. Ram and K. V. Mishra, "Beam Positioning for UAV Communications using On-Board 802.11ad Radar," IEEE SAM 2022.

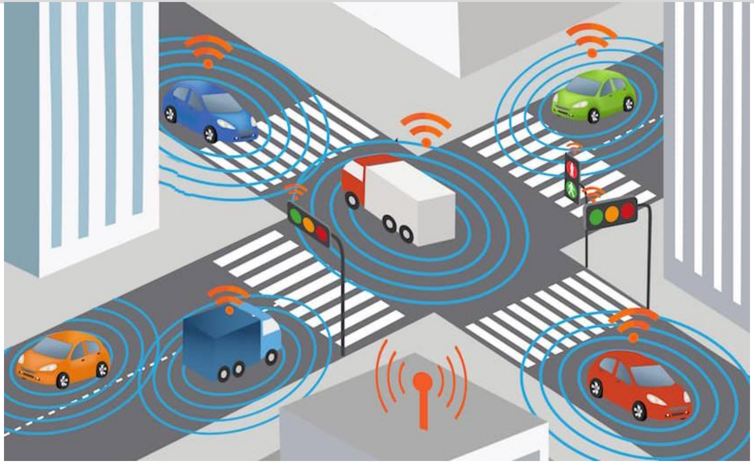
Courtesy: Species II



Spectral Co-Existence
Dual-Blind Deconvolution

Co-Existence Receiver





Passive Radar

Dynamic Communications

Problem: Neither the transmitted signals nor the channels are known

E. Vargas, K. V. Mishra, R. Jacome, B. M. Sadler and H. Arguello, “Dual-Blind Deconvolution for Overlaid Radar-Communications Systems,” arXiv preprint arXiv:2208.04381, 2022.
E. Vargas, K. V. Mishra, R. Jacome, B. M. Sadler and H. Arguello, “Joint radar-communications processing from a dual-blind deconvolution perspective,” IEEE ICASSP, 2022.

Dual-Blind Deconvolution Problem

$$y(t) = x_r(t) * h_r(t) + x_c(t) * h_c(t)$$

Transmitted radar signal

$$\sum_{p=0}^{P-1} s(t - pT)$$

Radar Channel

$$\sum_{\ell=0}^{L-1} [\alpha_r]_\ell \delta(t - [\tilde{\tau}_r]_\ell)e^{-j2\pi[\tilde{\nu}_r]_\ell t}$$

Transmitted communications signal

$$\sum_{p=0}^{P-1} \sum_{k=0}^{K-1} [g_p]_k e^{-j2\pi k\Delta f(t-pT)}$$

Communications channels

$$\sum_{q=0}^{Q-1} [\alpha_c]_q \delta(t - [\tilde{\tau}_c]_q)e^{-j2\pi[\tilde{\nu}_c]_q t}$$

PRI T	Radar waveform $\boldsymbol{s}$
Propagation paths Q	Symbols $\boldsymbol{g}$
Radar targets L	Time delay τ
Subcarriers K	Attenuation α
Transmitted pulses P	Doppler ν

$$[\boldsymbol{y}]_v = \sum_{\ell=0}^{L-1} [\alpha_r]_\ell [\boldsymbol{s}]_n e^{-j2\pi(n[\tau_r]_\ell + p[\nu_r]_\ell)} + \sum_{q=0}^{Q-1} [\alpha_c]_q [\boldsymbol{g}_p]_n e^{-j2\pi(n[\tau_c]_q + p[\nu_c]_q)}$$

Unknown variables: set of channel parameters $\{\boldsymbol{\tau_r}, \boldsymbol{\nu_r}, \boldsymbol{\alpha_r}, \boldsymbol{\tau_c}, \boldsymbol{\nu_c}, \boldsymbol{\alpha_c}\}$ and the transmit signals $\boldsymbol{s}, \boldsymbol{g}$

Atomic norm minimization framework

- Leveraging the sparse nature of the channels, we use ANM framework for super-resolved estimations of continuous-valued channel parameters.

- We define the atomic sets as

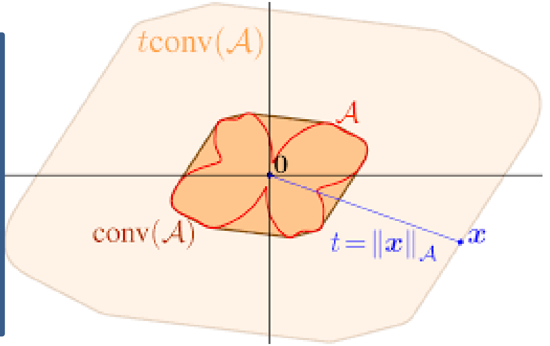
$$\mathcal{A}_r = \left\{\boldsymbol{u}\boldsymbol{a}(\boldsymbol{r})^H : \boldsymbol{r} \in [0,1)^2, ||\boldsymbol{u}||_2 = 1\right\}$$
$$\mathcal{A}_c = \left\{\boldsymbol{v}\boldsymbol{a}(\boldsymbol{c})^H : \boldsymbol{c} \in [0,1)^2, ||\boldsymbol{v}||_2 = 1\right\}$$

- The corresponding atomic norm are given by

$$||\boldsymbol{Z}_r||_{\mathcal{A}_r} = \inf_{[\alpha_r]_\ell, \boldsymbol{r}_\ell \in [0,1]^2, ||\boldsymbol{u}||_2 = 1} \{\textstyle\sum_\ell |[\alpha_r]_\ell| \,|\boldsymbol{Z}_r = \sum_\ell [\alpha_r]_\ell \boldsymbol{a}(\boldsymbol{r}_\ell)\boldsymbol{u}^H\}$$
$$||\boldsymbol{Z}_c||_{\mathcal{A}_c} = \inf_{[\alpha_c]_q, \boldsymbol{c}_q \in [0,1]^2, ||\boldsymbol{v}||_2 = 1} \{\textstyle\sum_q |[\alpha_c]_q| \,|\boldsymbol{Z}_c = \sum_q [\alpha_c]_q \boldsymbol{a}(\boldsymbol{c}_q)\boldsymbol{v}^H\}$$

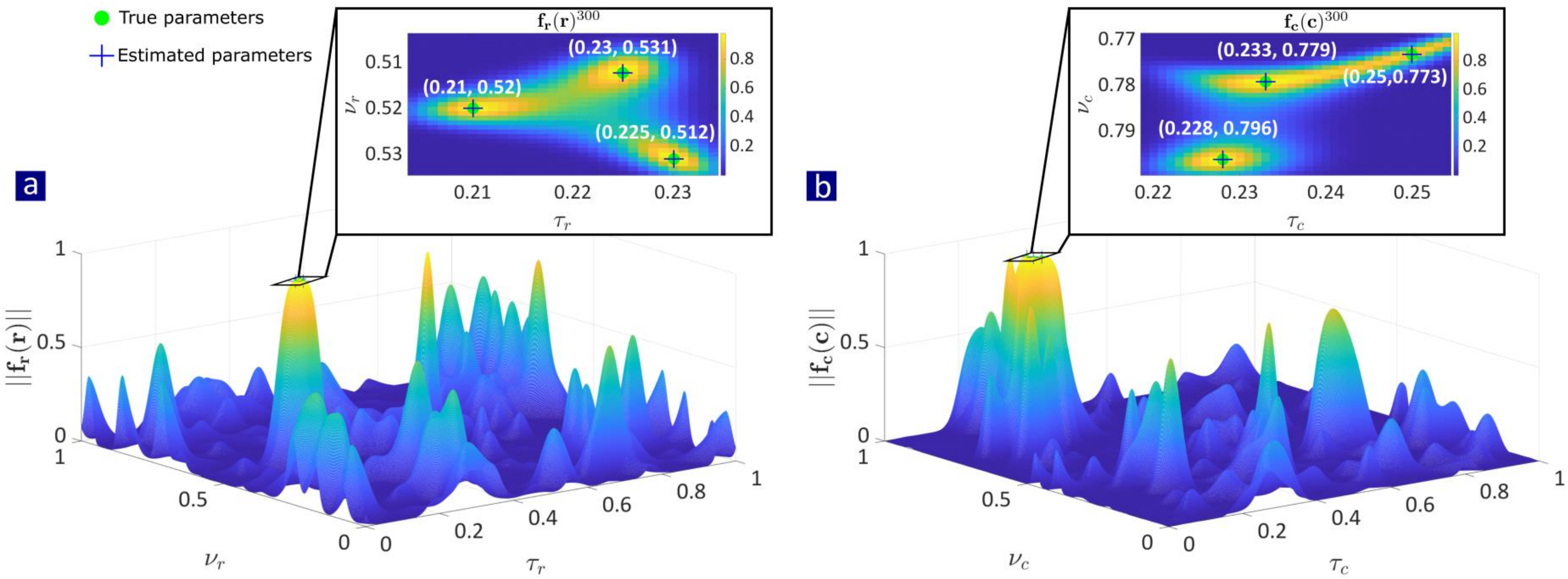
- The primal optimization problem is given by

$$\underset{\boldsymbol{Z}_r, \boldsymbol{Z}_c}{\text{minimize}} ||\boldsymbol{Z}_r||_{\mathcal{A}_r} + ||\boldsymbol{Z}_c||_{\mathcal{A}_c} \text{ subject to } \boldsymbol{y} = \aleph_r(\boldsymbol{Z}_r) + \aleph_c(\boldsymbol{Z}_c)$$

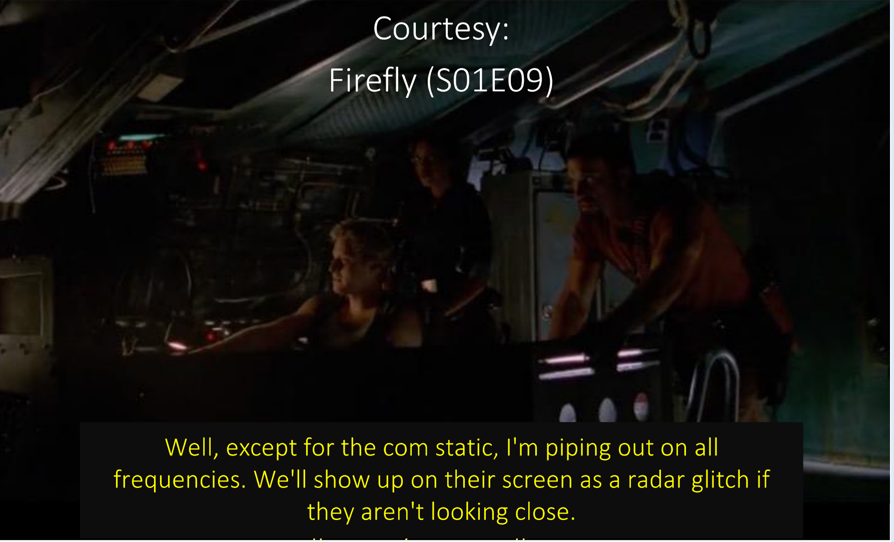


E. Vargas, K. V. Mishra, R. Jacome, B. M. Sadler and H. Arguello, "Dual-Blind Deconvolution for Overlaid Radar-Communications Systems," arXiv preprint arXiv:2208.04381, 2022.
E. Vargas, K. V. Mishra, R. Jacome, B. M. Sadler and H. Arguello, "Joint radar-communications processing from a dual-blind deconvolution perspective," IEEE ICASSP, 2022.

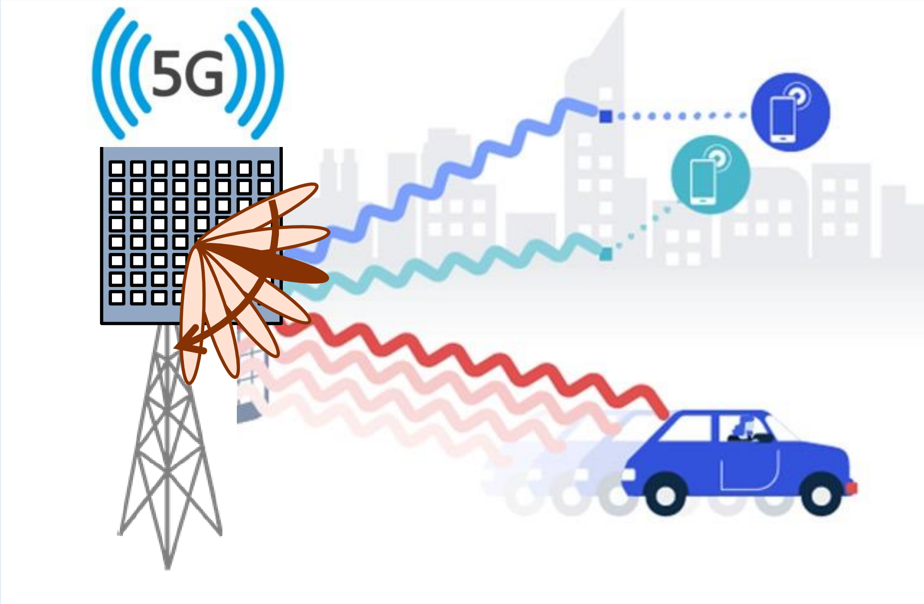
Localization for single Rx



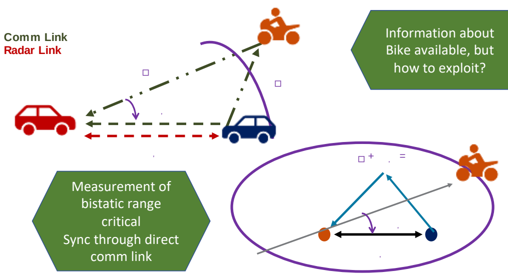
E. Vargas, K. V. Mishra, R. Jacome, B. M. Sadler and H. Arguello, "Dual-Blind Deconvolution for Overlaid Radar-Communications Systems," arXiv preprint arXiv:2208.04381, 2022.
E. Vargas, K. V. Mishra, R. Jacome, B. M. Sadler and H. Arguello, "Joint radar-communications processing from a dual-blind deconvolution perspective," IEEE ICASSP, 2022.



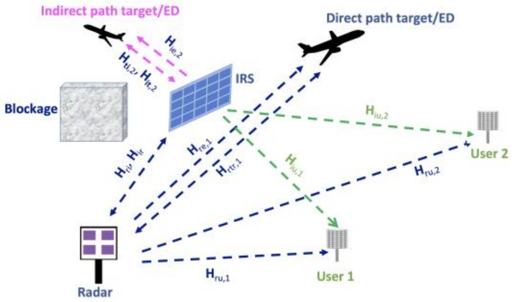
Other Distributed ISAC Architectures



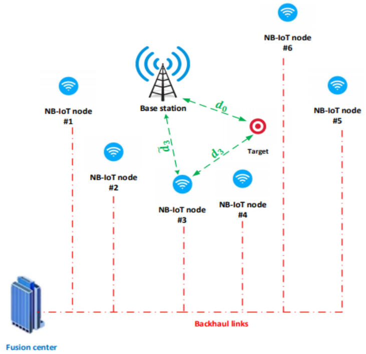
Emerging Distributed JRC/ISAC Trends



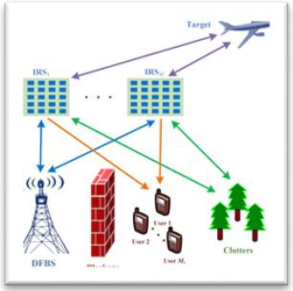
Sensor Fusion



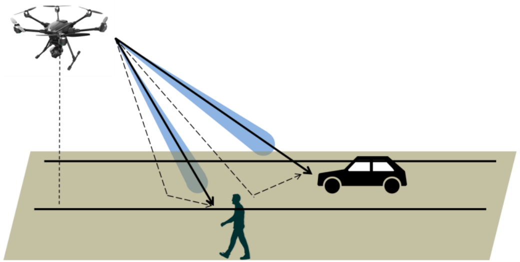
Secure IRS-Aided DFRC



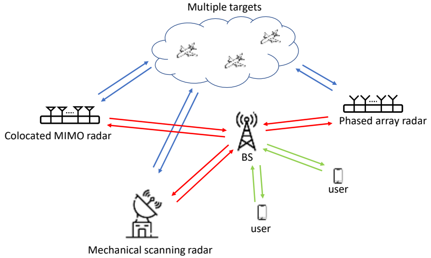
Passive ISAC



IRS-Aided JRC



Drone-Borne ISAC



Heterogenous ISAC

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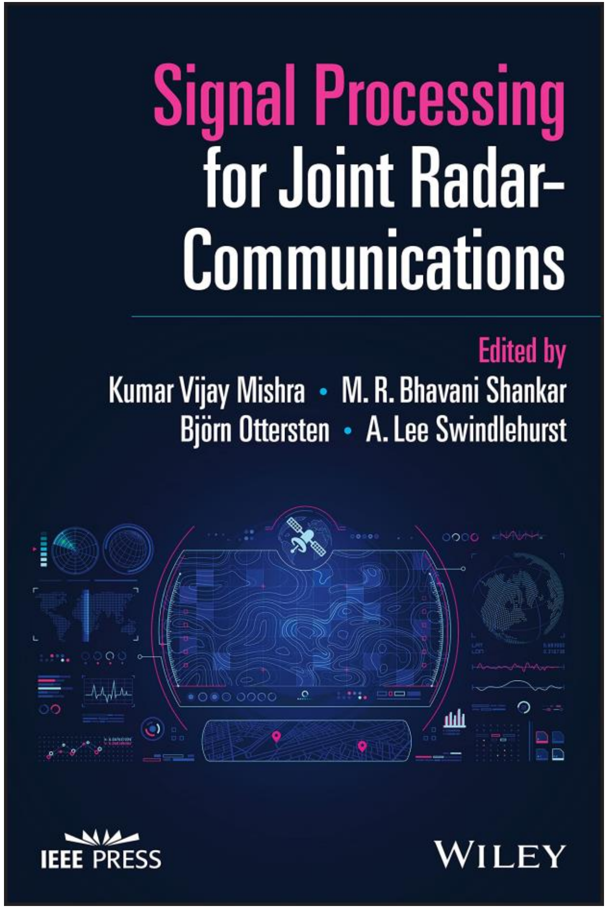
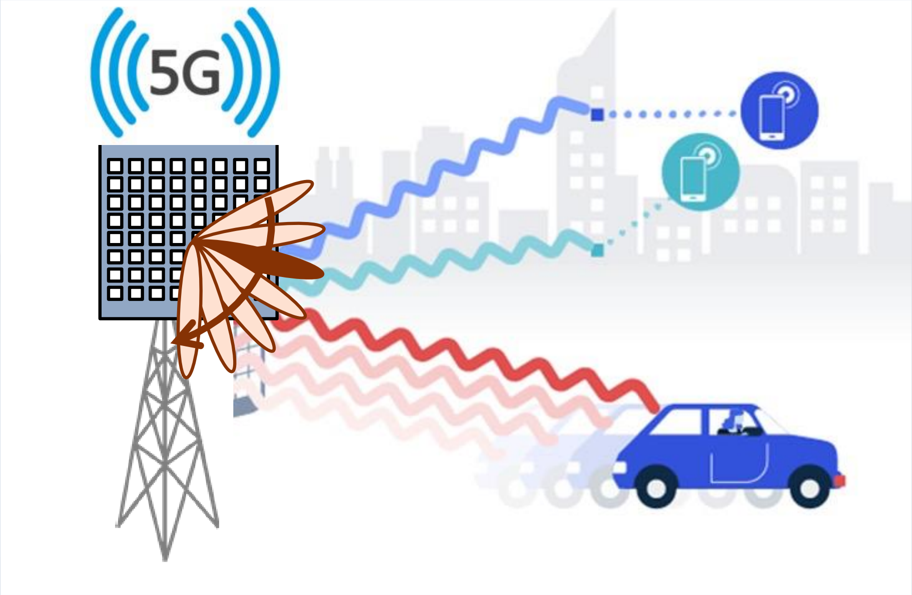
Thank you!


Signal Processing
for Joint Radar-
Communications
Edited by
Kumar Vijay Mishra • M. R. Bhavani Shankar
Björn Ottersten • A. Lee Swindlehurst
IEEE PRESS
WILEY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