Distributed Integrated Sensing and Communications

Kumar Vijay Mishra

United States DEVCOM Army Research Laboratory

IEEE Vehicular Technology Society Distinguished Lecture

Chicago Section Chapter

21 July 2023

About the speaker

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- Research Fellow, SnT, U of Luxembourg
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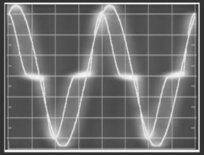
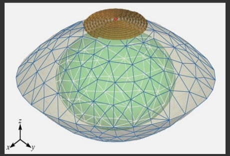
- Vice-Chair, URSI Commission C
- Editor, IEEE Transactions on Aerospace and Electronic Systems
- Vice-Chair, IEEE Synthetic Aperture Standards Committee; Member, IEEE SPS SAM, SPS TWG on Synthetic Apertures, INGR IEEE International Network Generations Roadmap, AESS Radar Systems Panel
- Founding member, 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

Acknowledgements

- ARL: Brian M. Sadler
- U of Luxembourg: M. R. Bhavani Shankar, Bjorn Ottersten, Ahmet M. Elbir, Tong Wei, Linlong Wu, Julian Krebs, Ahmad Gharanjik
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The National Academies of SCIENCES ENGINEERING MEDICINE

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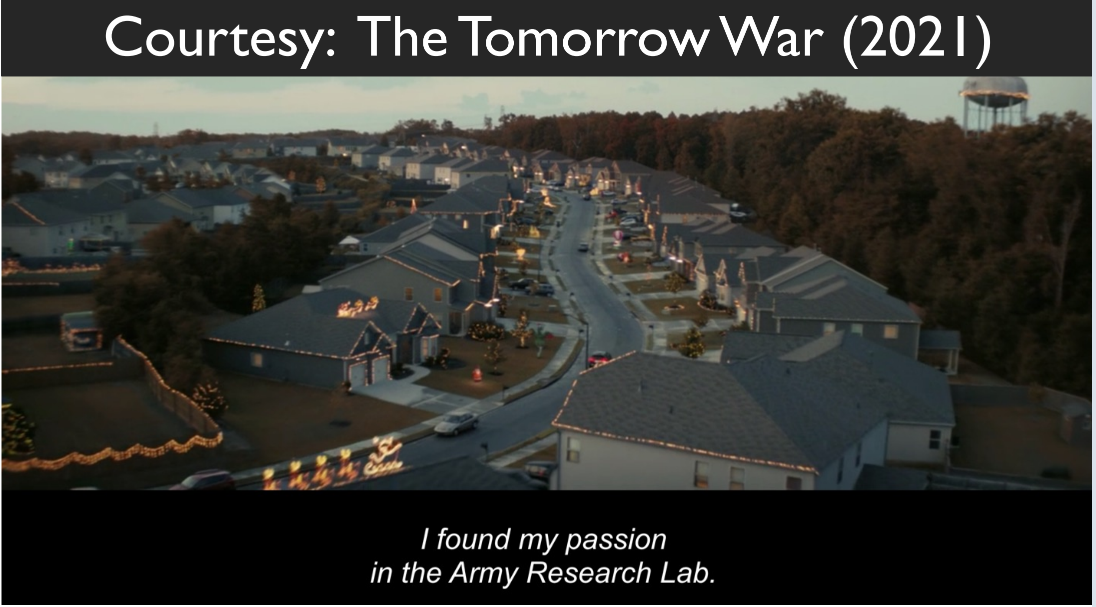
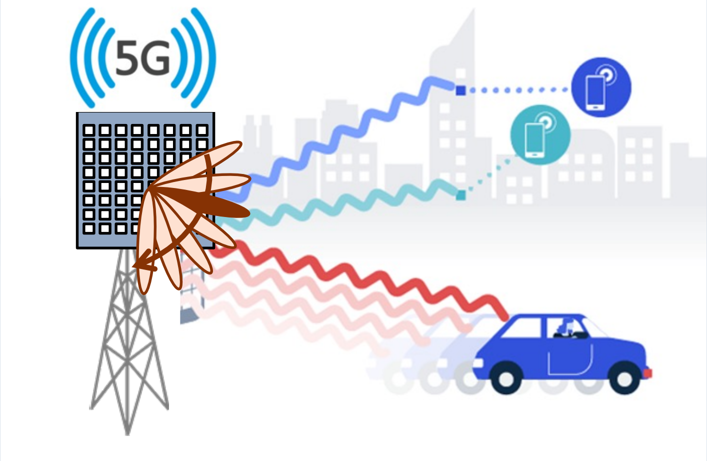
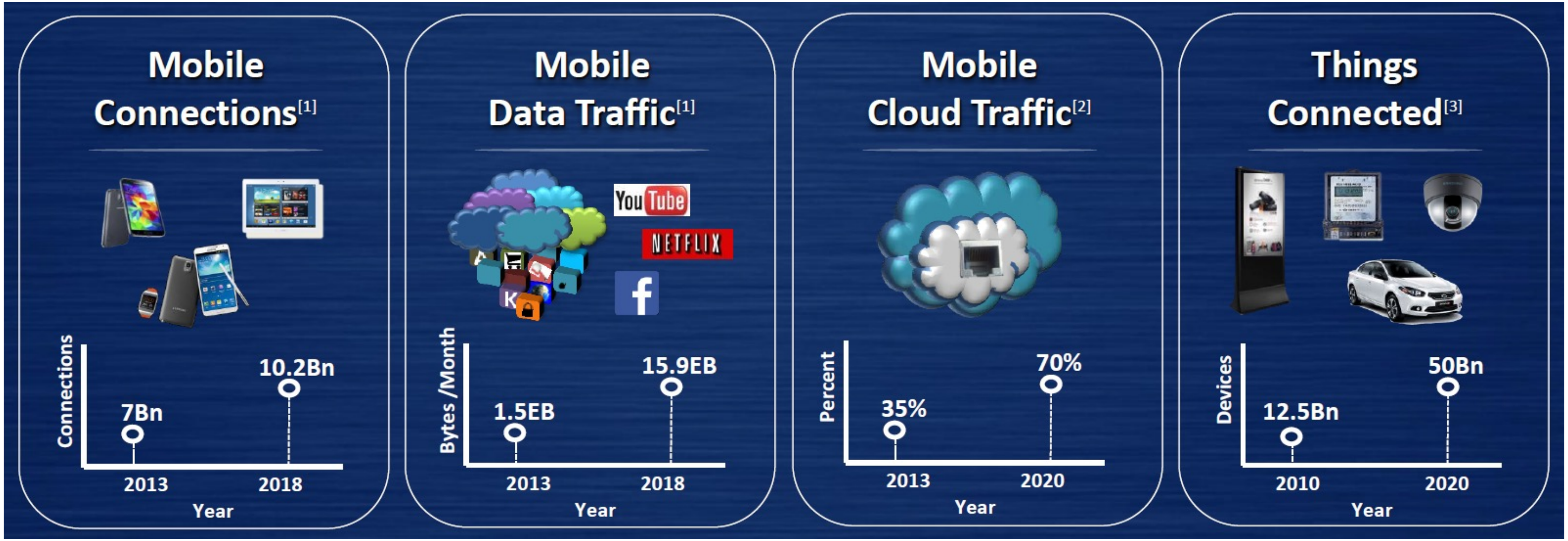

Courtesy: The Tomorrow War (2021)
I found my passion
in the Army Research Lab.


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

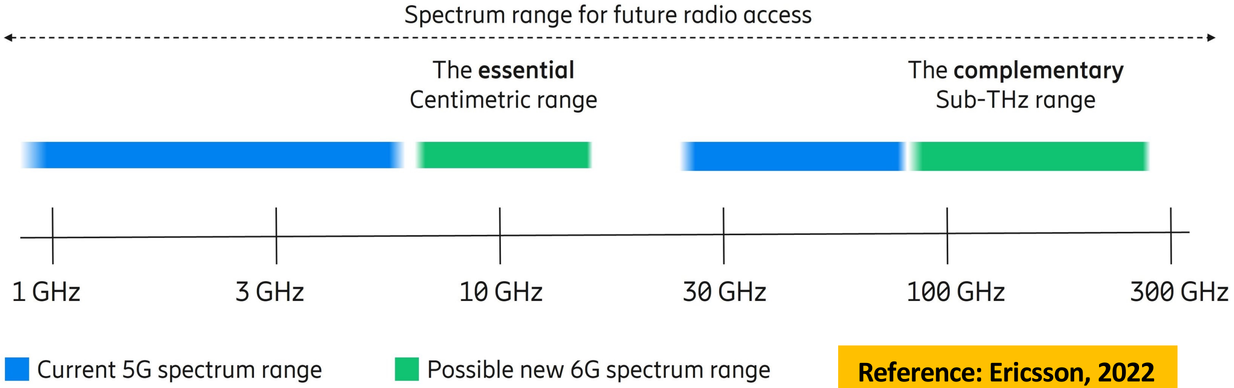
How to Meet Demand in Current Landscape?

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

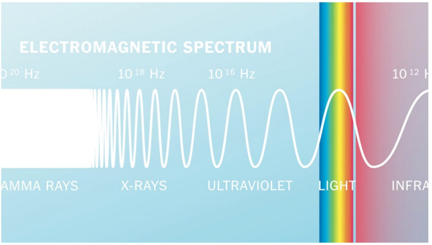
July 6, 1986

2012

The New York Times

Carriers Warn of Crisis in Mobile Spectrum

Give this article



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

Sign In

Wealth

Billionaires Musk, Ergen and Dell Brawling Over Spectrum at FCC

By Todd Shields + Follow

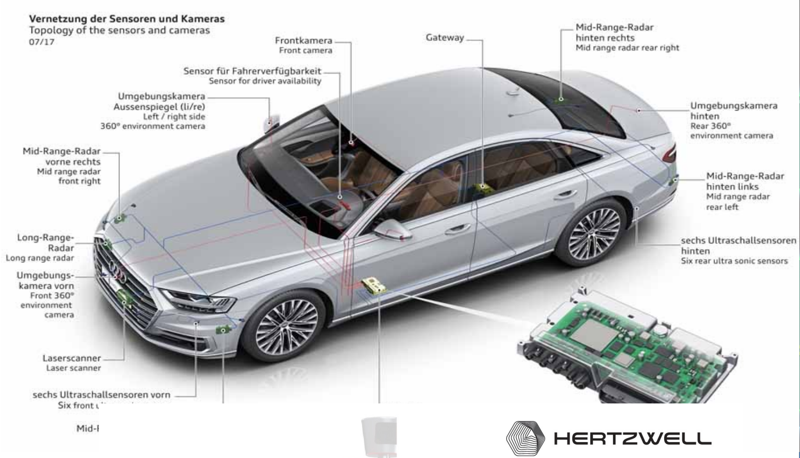
October 9, 2021, 8:45 AM EDT

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

LIVE ON BLOOMBERG
Watch Live TV >
Listen to Live Radio >
Bloomberg Television

Sensor-Driven Vehicles

(1)



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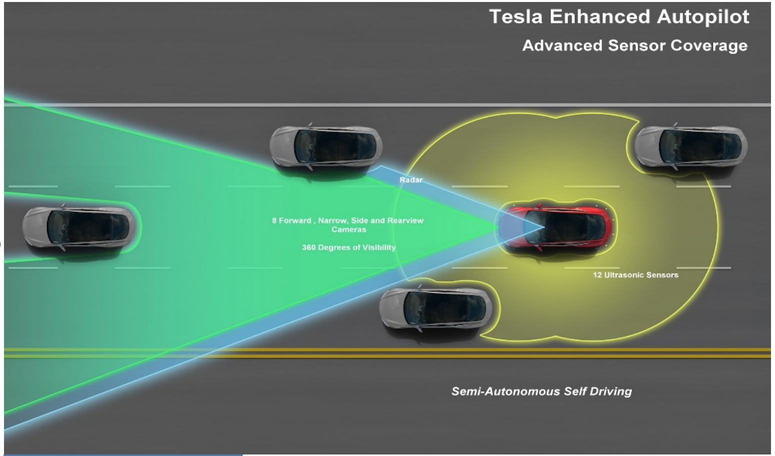

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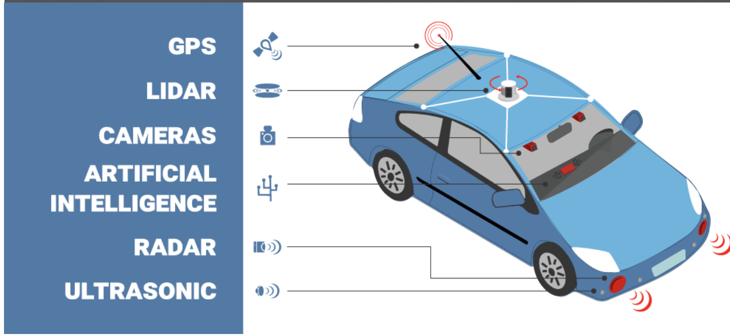
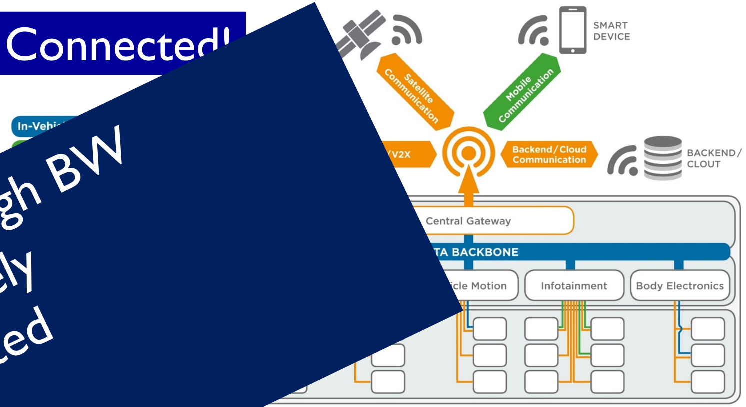


In Addition, Modern Cars are …

Software-Managed

… and Connected!



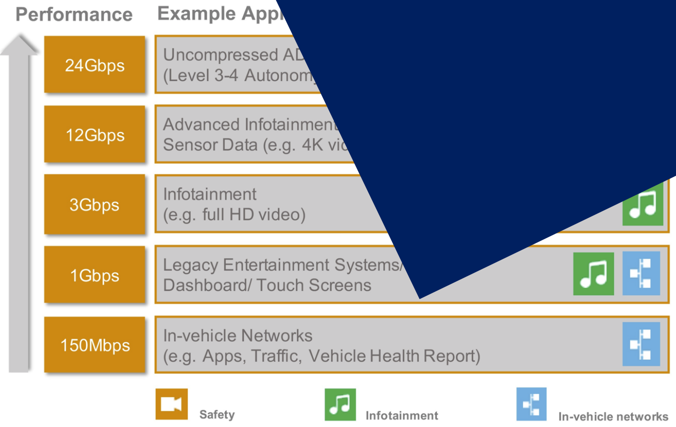
Autonomous Vehicles need high BW

1) To sense accurately

2) To stay connected

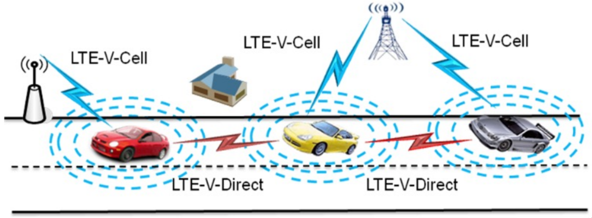
Q: Where is the BW?

…ge Data!



…ss technologies

- DSRC
- C-V2X

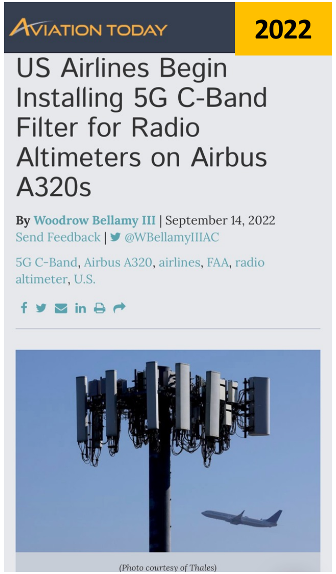


IEEE Spectrum Allocation

Modern radar/comms operate in an increasingly crowded RF spectrum

Radars need to use full bandwidth and undertake continuous transmissions

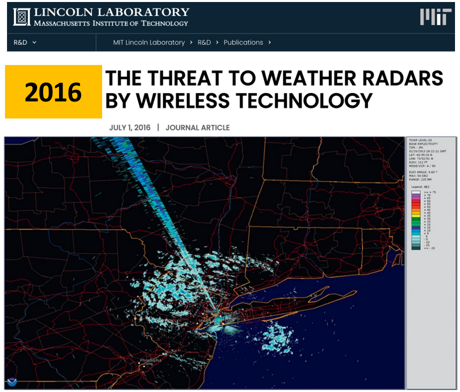
IEEE Radar band	VHF/UHF [30 MHz – 1 GHz]	L [1-2 GHz]	S [2-4 GHz]	C [4-8 GHz]	X [8-12 GHz]	Ku, K, Ka ,V, W [12-300 GHz]
Examples of radar usage	FOPEN	ARSR	ASR, NEXRAD	TDWR	CASA	Automotive radars, cloud radars
Co-existing comms	TV/broadcast/ 802.11ah/f	WiMAX, JTIDS	LTE	802.11a/ ac	LTE	802.11ad, mmwave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



DARPA

Shared Spectrum Access for Radar and Communications (SSPARC)

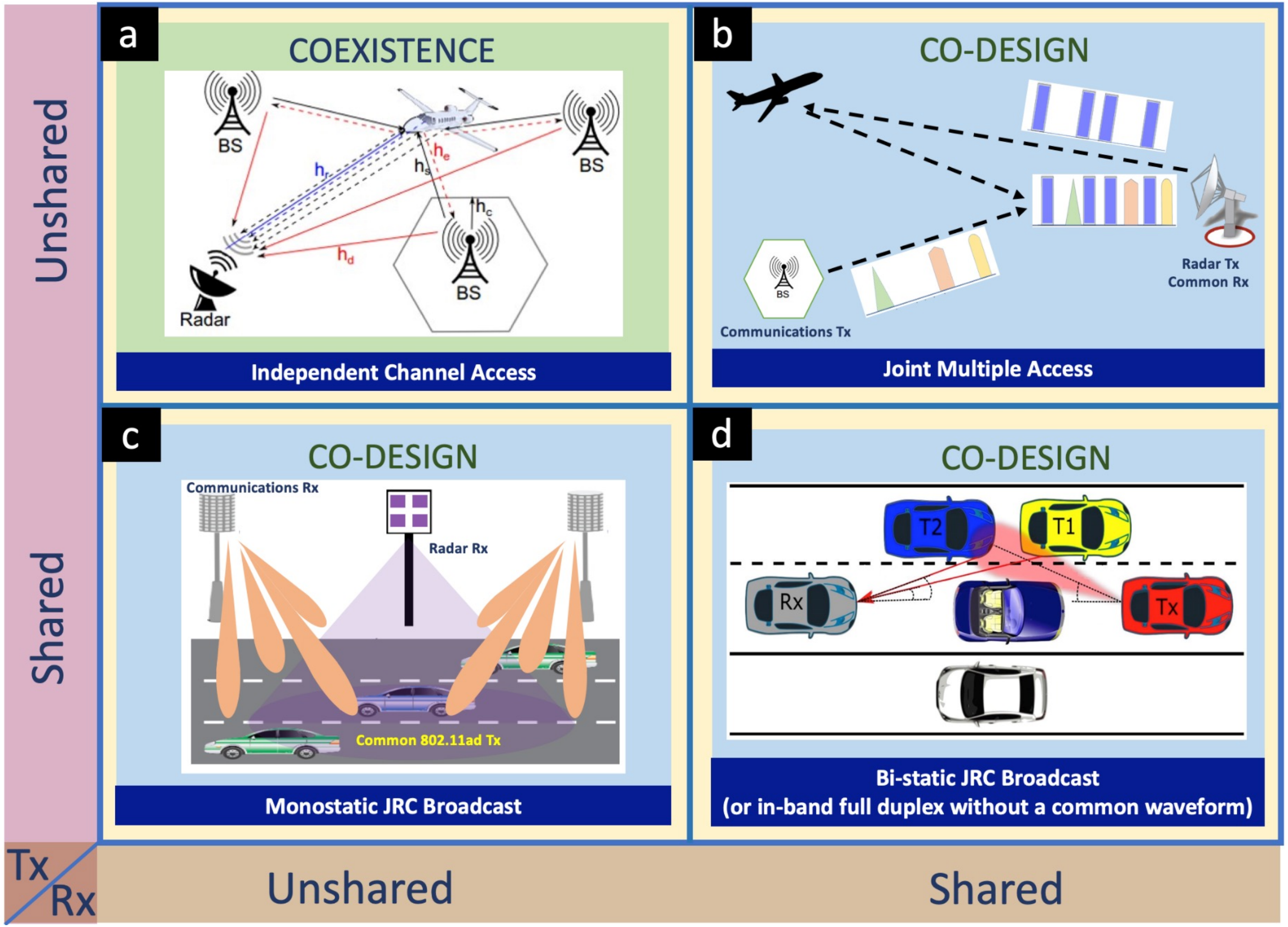
Platforms for Advanced Wireless Research



NRDZ National Radio Dynamic Zone

RFDATA FACTORY

Integrated Sensing and Communications (ISAC) Topologies

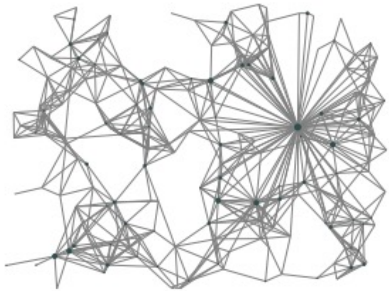


More ISAC Topologies

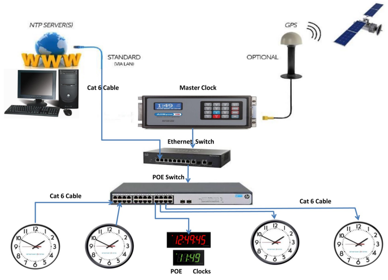
Channel Access	Hardware	Waveform
Independent Coordinated Joint Shared	Separate Tx & Rx Same Tx, Common Rx Common Tx, Same Rx Common Tx & Rx	Separate Common Resource-shared
Location	**Performance/Functionality**	**Specialized**
Colocated Bi-static Distributed Networked Heterogeneous	Radar-centric Comms-centric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

Distributed ISAC Considerations

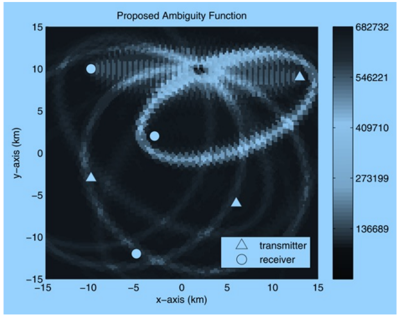
Challenge: Future networks will be more decentralized and edge-focused
Current research devoted to colocated/centralized ISAC



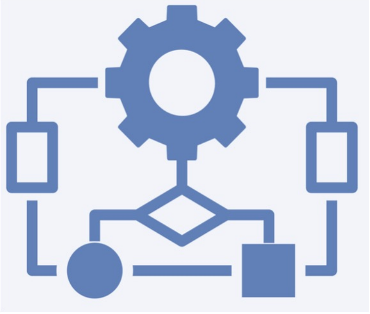
Complexity



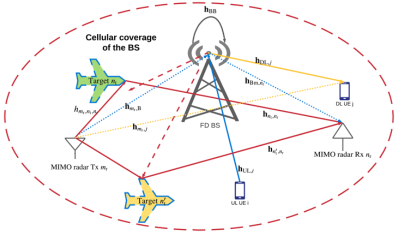
Synchronization



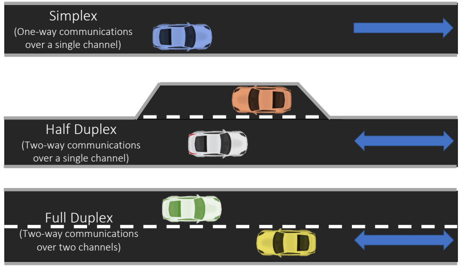
Statistical Design



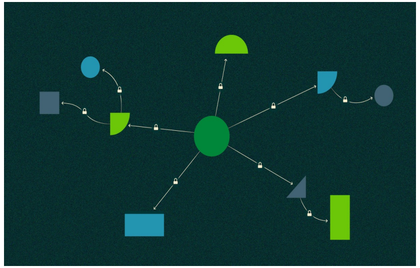
Speed



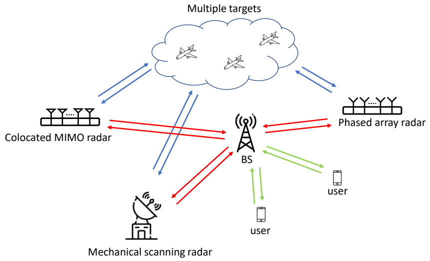
Data Association



Duplexing



Fusion Center



Architectures

Outline

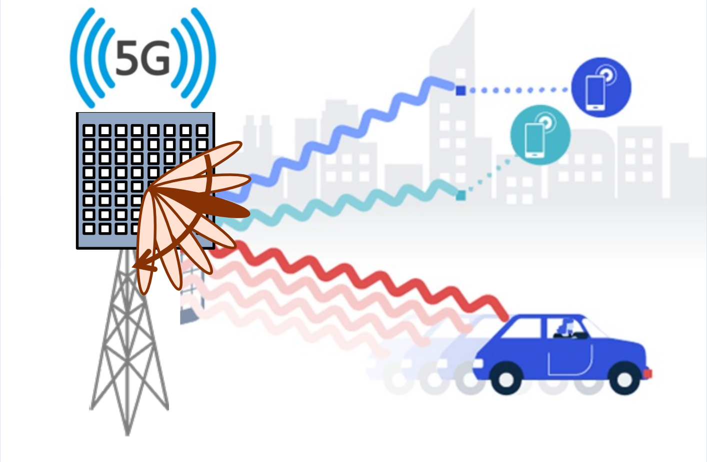
Applications — Motivation & Challenges

Comms-Aided Weather Radar, Full-Duplex ISAC

Ill-Posedness — Dual-Blind Deconvolution

Architectures — IRS-Aided, THz, Passive, Heterogeneous, Secure ISAC

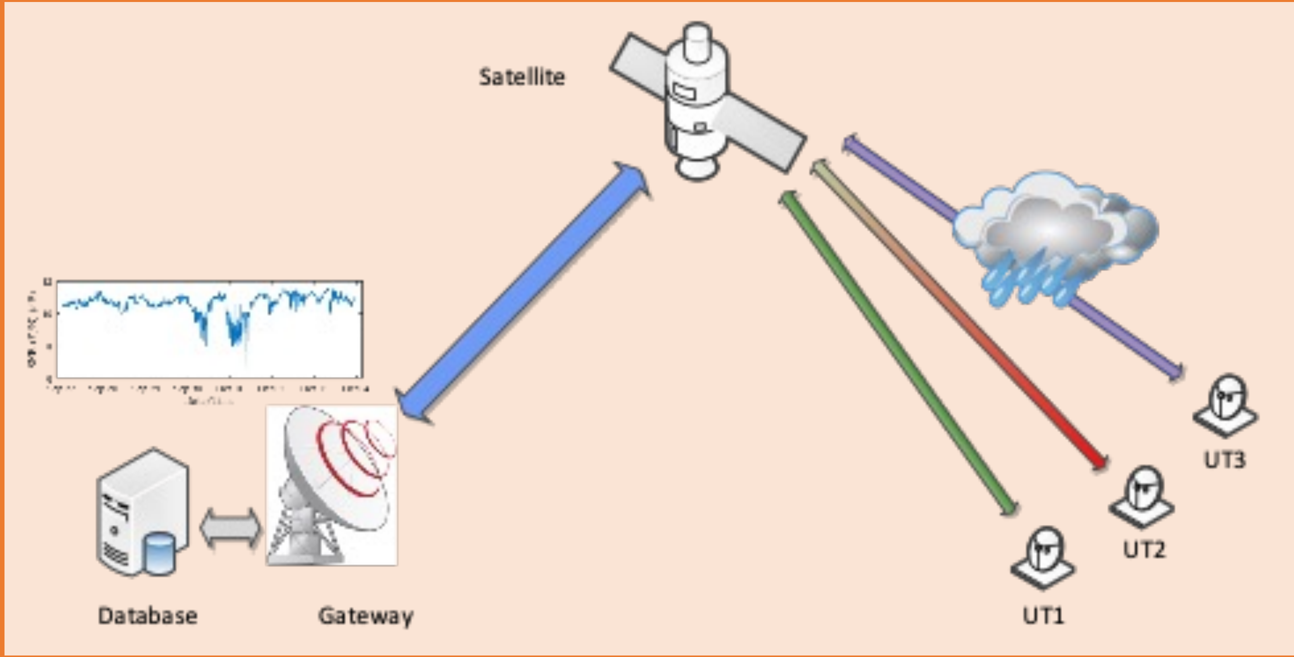
Courtesy: Citadel (S01E06)



Introductory Example

Comms-Aided Weather Radar

Opportunistic Use of Comms for Radar Purposes



Millimeter-wave satellite communications terminals offer an alternative to rainrate (R) estimation

Wide coverage through ~300,000 UTs spread across Europe and 2 million worldwide.

Signaling data already aggregated in a database

Low capital/operational expenditure

Challenge: How to estimate R from attenuation data

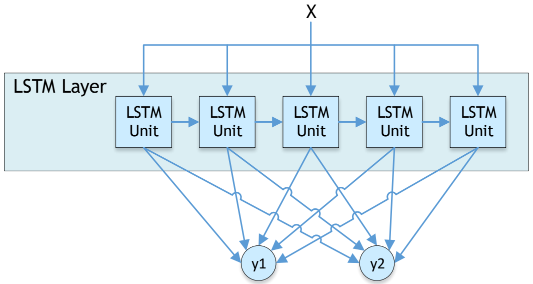
[1] K. V. Mishra, A. Gharanjik, M. R. B. Shankar, and B. Ottersten, "Deep learning framework for precipitation retrievals from communication satellites" European Conference on Radar in Meteorology & Hydrology, 2018.
[2] A. Gharanjik, K. V. Mishra, M. R. B. Shankar and B. Ottersten, "Learning-based rainfall estimation via communication satellite links," IEEE Statistical Signal Processing Workshop, 2018.
[3] K. V. Mishra, M. R. B. Shankar and B. Ottersten, "Deep rainrate estimation from highly attenuated downlink signals of ground-based communications satellite terminals," IEEE International Conference on Acoustics, Speech and Signal Processing, 2020.

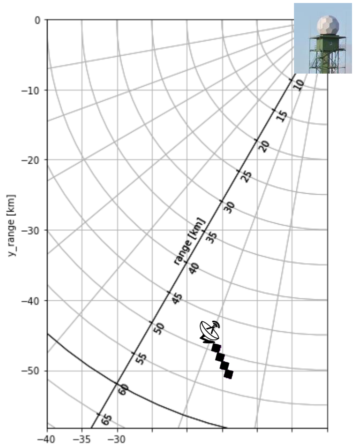
Deep-Learning-Based Rain-Rate Estimation

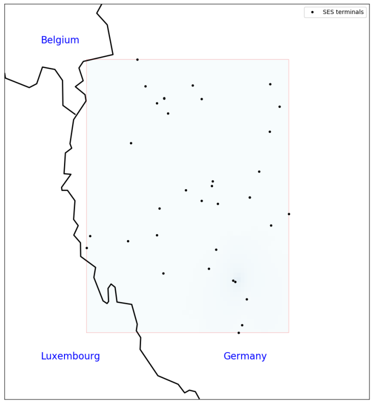
Millimeter-wave weather radars employ additional parameters to estimate R

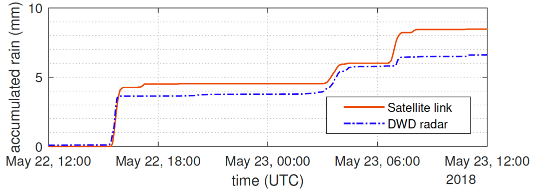
Wind shear, storm types and intensities perturb the linear R-Ah relationship

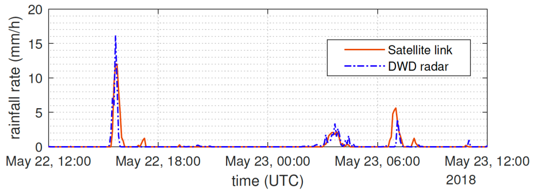
We turn to deep learning to estimate rainrate from comms UTs











[1] K. V. Mishra, A. Gharanjik, M. R. B. Shankar, and B. Ottersten, "Deep learning framework for precipitation retrievals from communication satellites" European Conference on Radar in Meteorology & Hydrology, 2018.

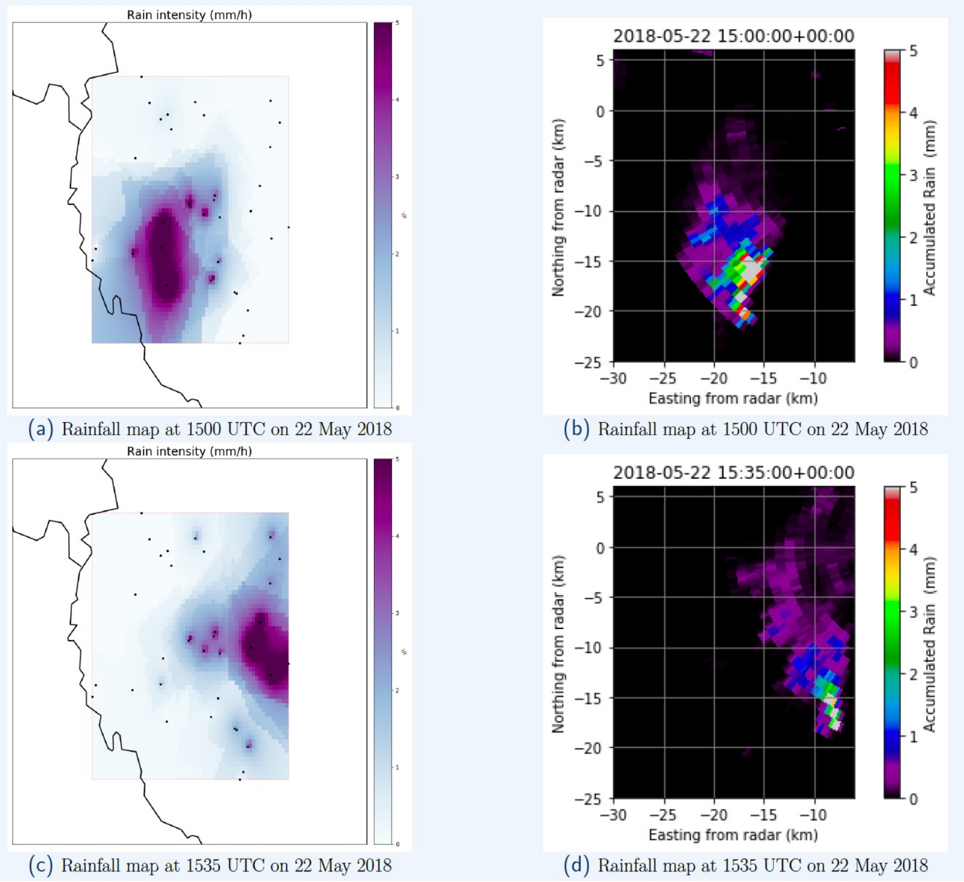
[2] K. V. Mishra, M. R. B. Shankar and B. Ottersten, "Deep rainrate estimation from highly attenuated downlink signals of ground-based communications satellite terminals," IEEE International Conference on Acoustics, Speech and Signal Processing, 2020.

Rain-Map Comparison

UT-Based rain maps broadly follow the intensity and direction of the storm

Beneficial in weather-radar-denied environments

Low-cost solution that complements weather radars



(a) Rainfall map at 1500 UTC on 22 May 2018

(b) Rainfall map at 1500 UTC on 22 May 2018

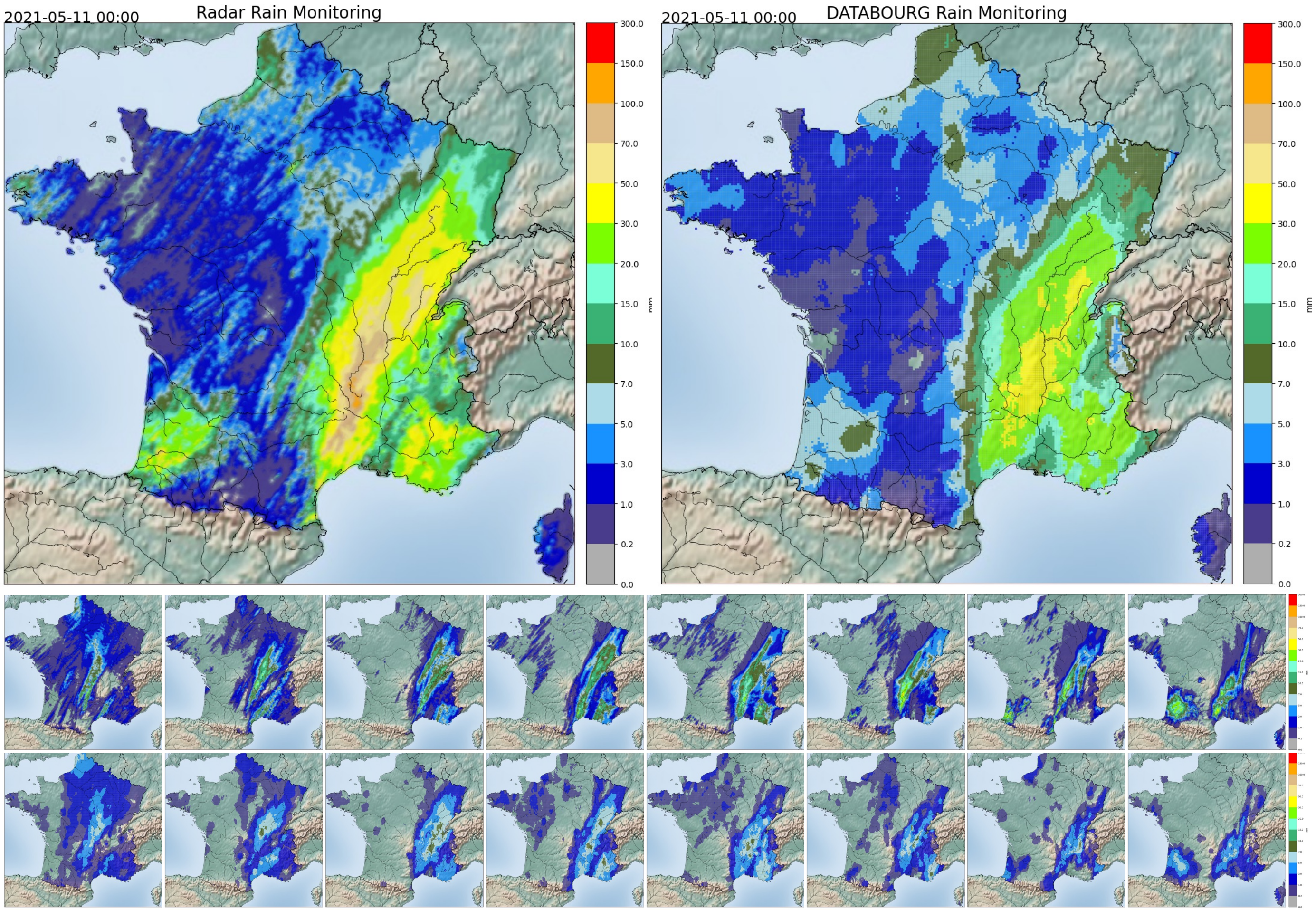
(c) Rainfall map at 1535 UTC on 22 May 2018

(d) Rainfall map at 1535 UTC on 22 May 2018

DATABOURG SYSTEMS

[1] K. V. Mishra, A. Gharanjik, M. R. B. Shankar, and B. Ottersten, “Deep learning framework for precipitation retrievals from communication satellites” European Conference on Radar in Meteorology & Hydrology, 2018.

Comparison to Radar



Radar

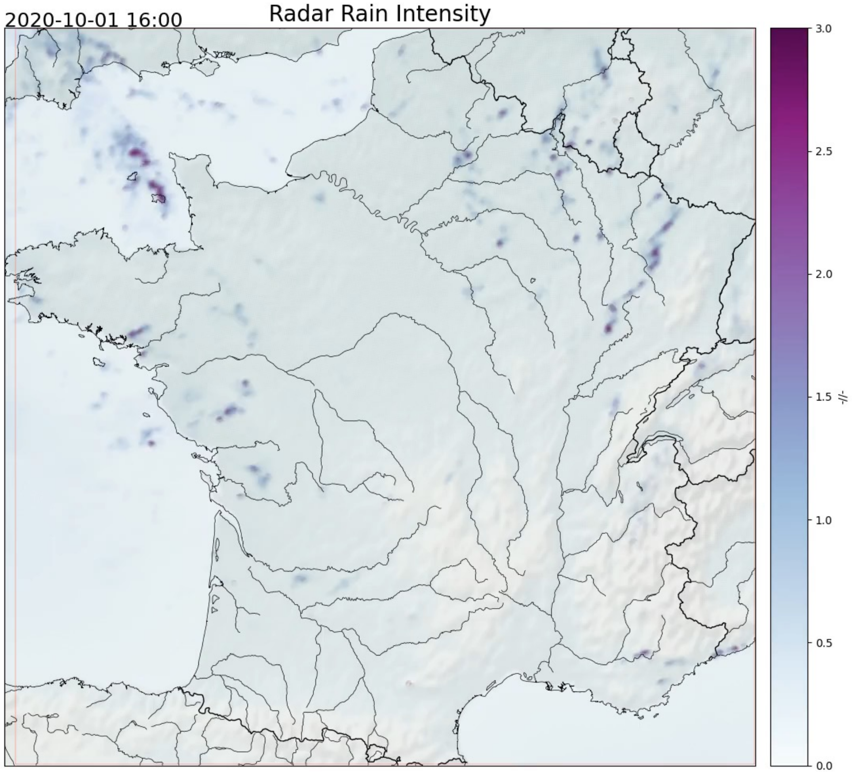
Sat

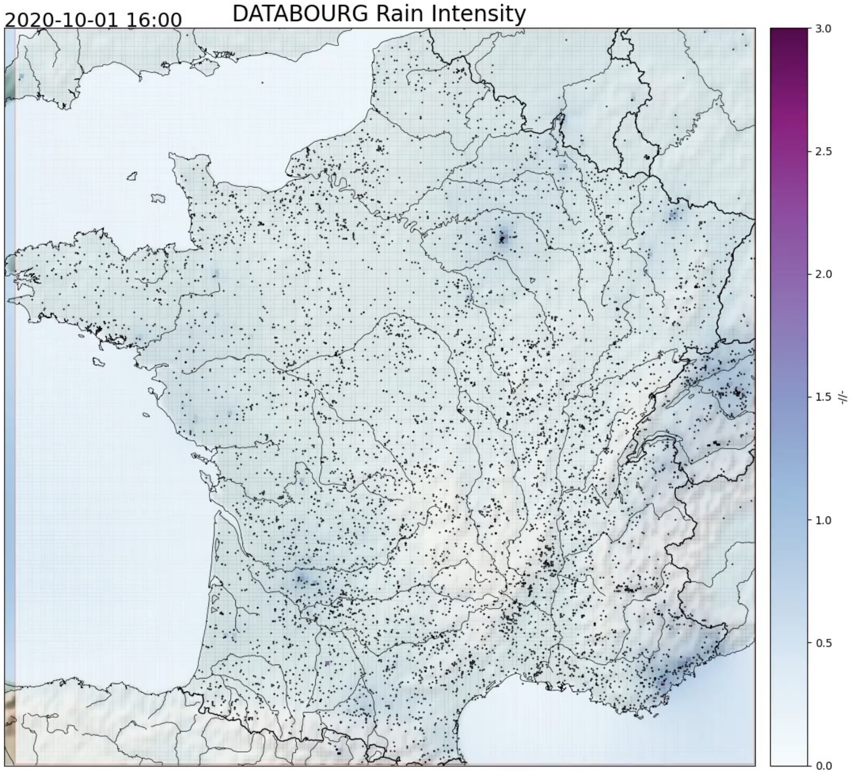
3:00 6:00 9:00 12:00 15:00 18:00 21:00 24:00

[1] J. Krebs, K. V. Mishra, A. Gharanjik, and M. R. B. Shankar, “Spatio-Temporal Rainfall Estimation from Communication Satellite Data using Graph Neural Networks,” European Geosciences Union General Assembly, 2022.

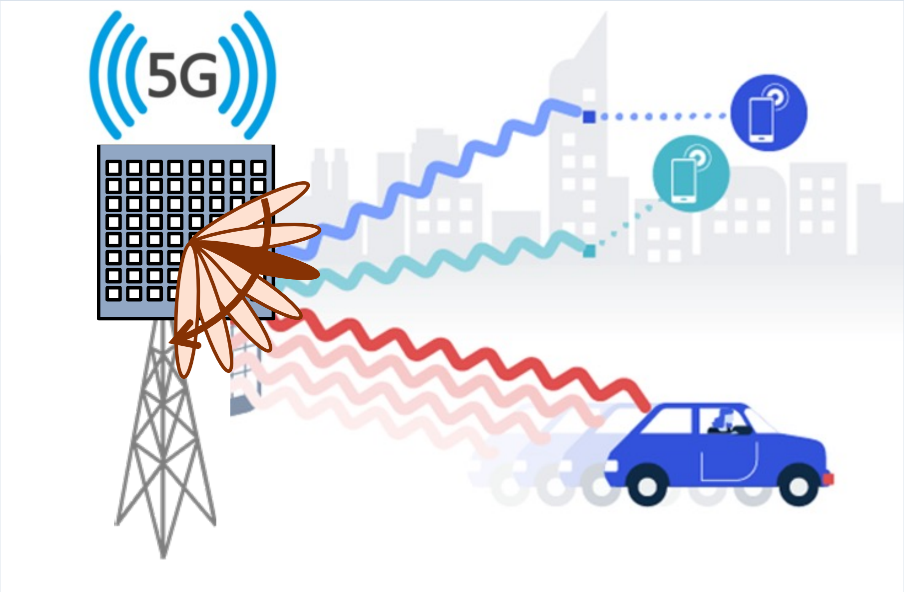
Comparison to Radar

CNN Training
October 1-3, 2020
Storm Alex



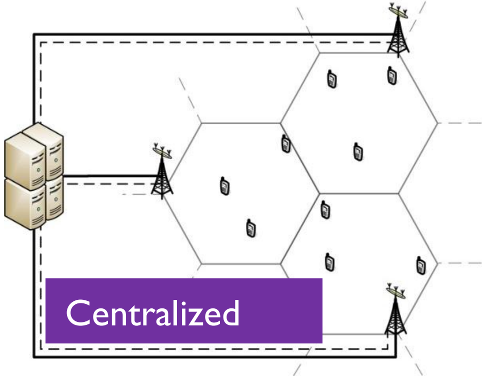


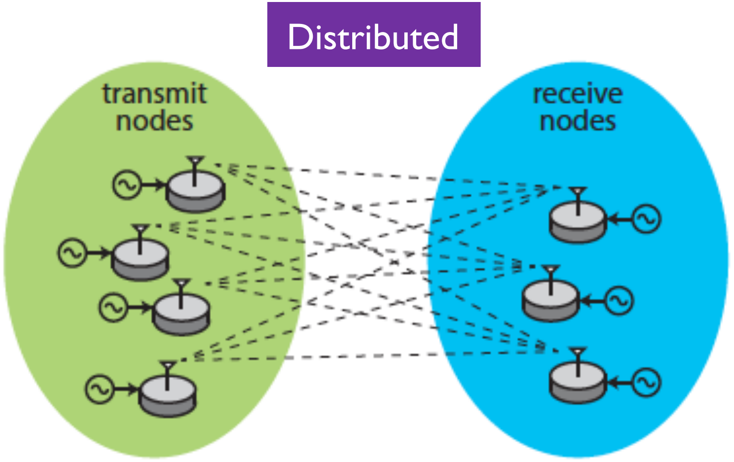
[1] J. Krebs, K. V. Mishra, A. Gharanjik, and M. R. B. Shankar, "Spatio-Temporal Rainfall Estimation from Communication Satellite Data using Graph Neural Networks," European Geosciences Union General Assembly, 2022.



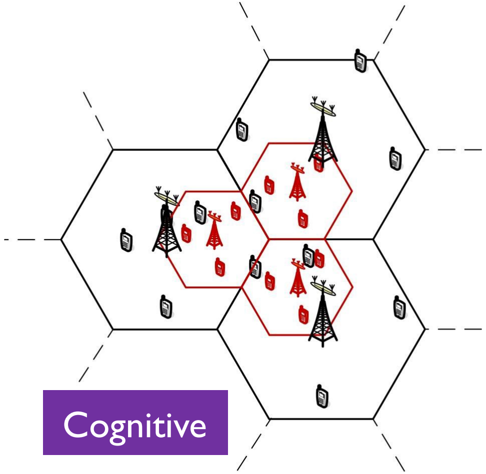
Distributed Systems

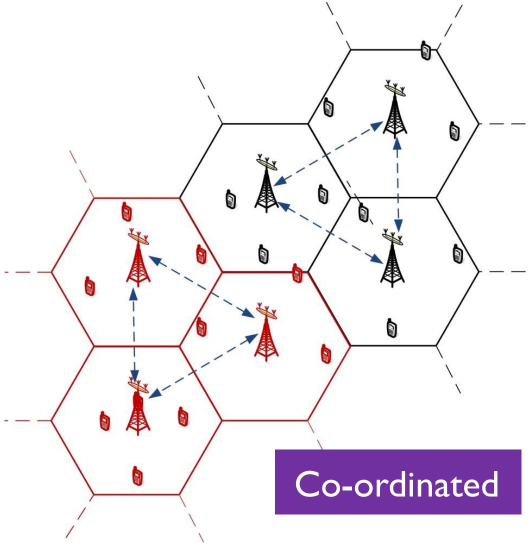
Non-colocated MIMO : Multi-cell, Distributed





© IEEE DOI: 10.1109/ITA.2014.6804225

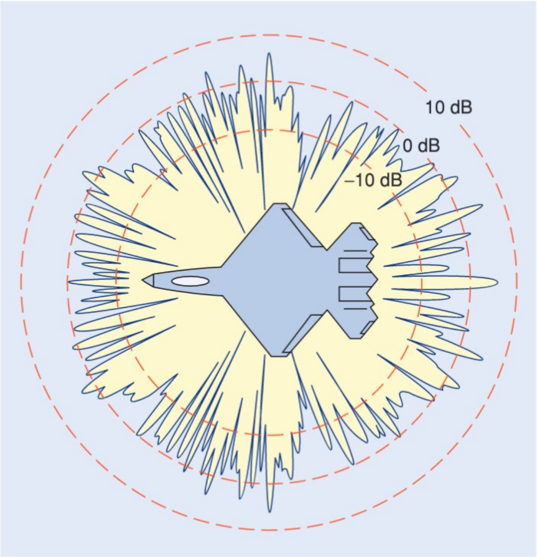


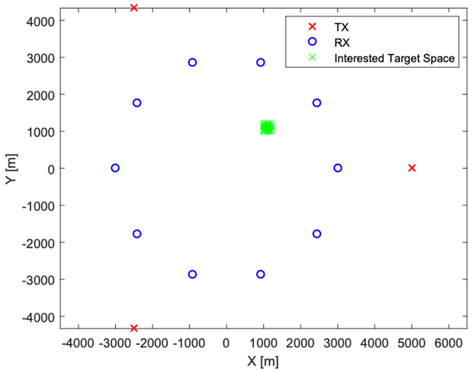


- Better service to the users at the cell edge
  - Assumes some infrastructure and protocol support
- Large virtual arrays or massive MIMO
  - Synchronization and scaling up

Widely Distributed MIMO Radar

- Exploits spatial diversity of the target
- Tx and Rx placed so far apart that target RCS appears different to each Tx-Rx pair
- Also called "Statistical MIMO" because RCS is modeled as a random variable (=radar channel is statistical)
- Practical applications include detection of stealth target who may have minimal backscatter in each direction

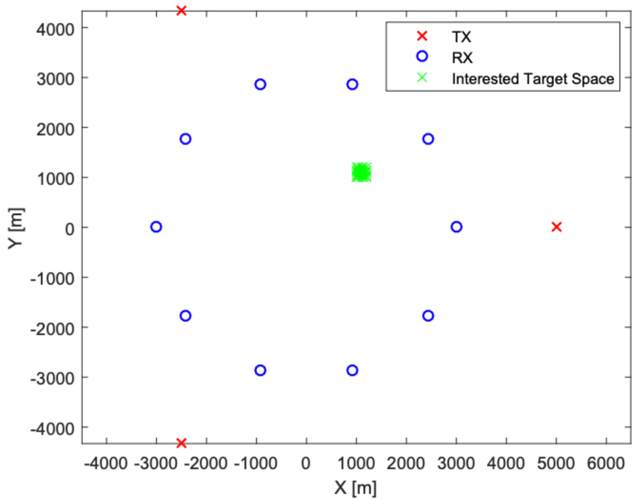




A. M. Haimovich, R. S. Blum and L. J. Cimini, "MIMO Radar with Widely Separated Antennas," in IEEE Signal Processing Magazine, vol. 25, no. 1, pp. 116-129, 2008
S. Sun, K. V. Mishra and A. P. Petropulu, "Target Estimation by Exploiting Low Rank Structure in Widely Separated MIMO Radar," RadarConf 2019.

Widely Distributed MIMO Radar: Model with Doppler

- Assume that the radar target scene consists of K targets distributed in an area denoted by a set of coordinates S, sharing the same 2-D plane.
- Time delay $\tau_{mn}^{(k)}$ at n-th Rx w.r.t. m-th Tx is linearly proportional to the target's location $\mathbf{p}^{(k)}$:

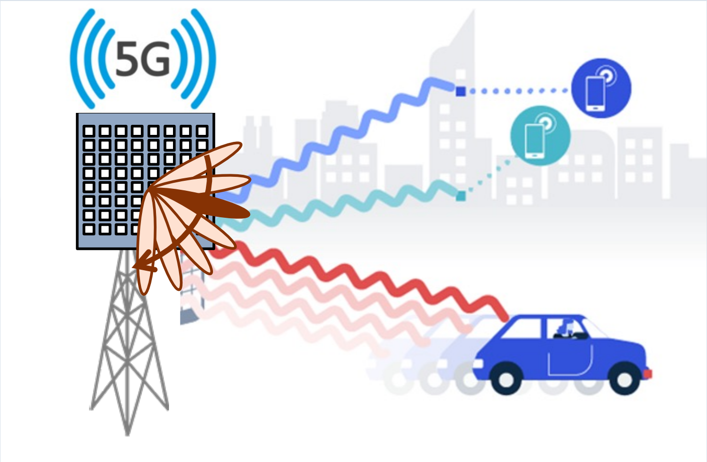


$$\tau_{mn}^{(k)} = \frac{\left\|\mathbf{p}^{(k)} - \mathbf{p}_t^{(m)}\right\| + \left\|\mathbf{p}^{(k)} - \mathbf{p}_r^{(n)}\right\|}{c},$$

- Doppler frequency $f_{mn}^{(k)}$ is proportional t the target's radial velocity $\mathbf{v}^{(k)}$:

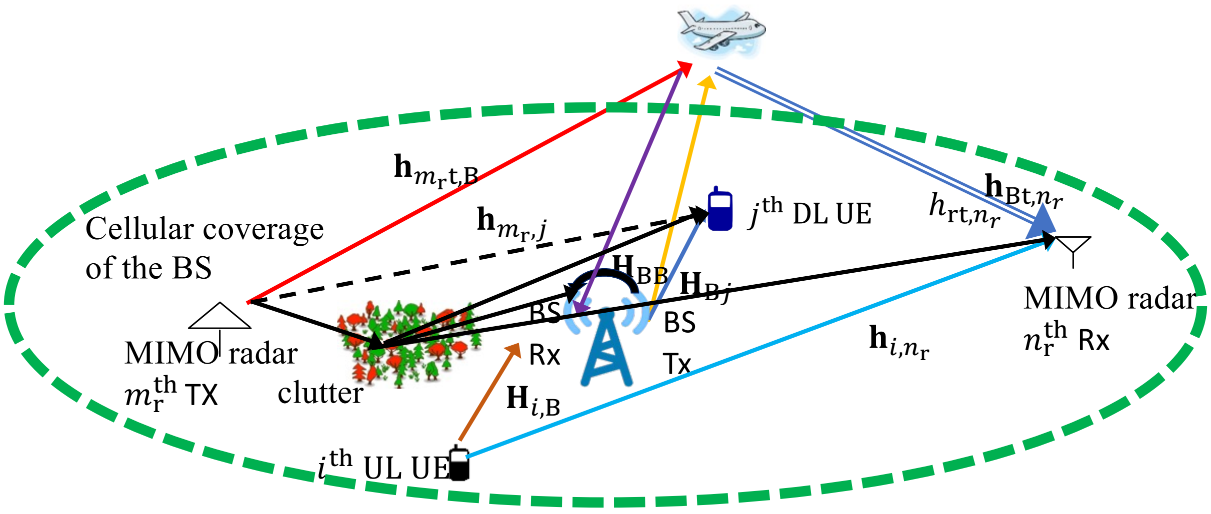
$$f_{mn}^{(k)} = \frac{f_m}{c}\left(\frac{\left\langle \boldsymbol{\nu}^{(k)}, \mathbf{p}^{(k)} - \mathbf{p}_t^{(m)}\right\rangle}{\left\|\mathbf{p}^{(k)} - \mathbf{p}_t^{(m)}\right\|} + \frac{\left\langle \boldsymbol{\nu}^{(k)}, \mathbf{p}^{(k)} - \mathbf{p}_r^{(n)}\right\rangle}{\left\|\mathbf{p}^{(k)} - \mathbf{p}_r^{(n)}\right\|}\right)$$

S. Sun, K. V. Mishra and A. P. Petropulu, "Target Estimation by Exploiting Low Rank Structure in Widely Separated MIMO Radar," RadarConf 2019.



Distributed IBFD ISAC

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

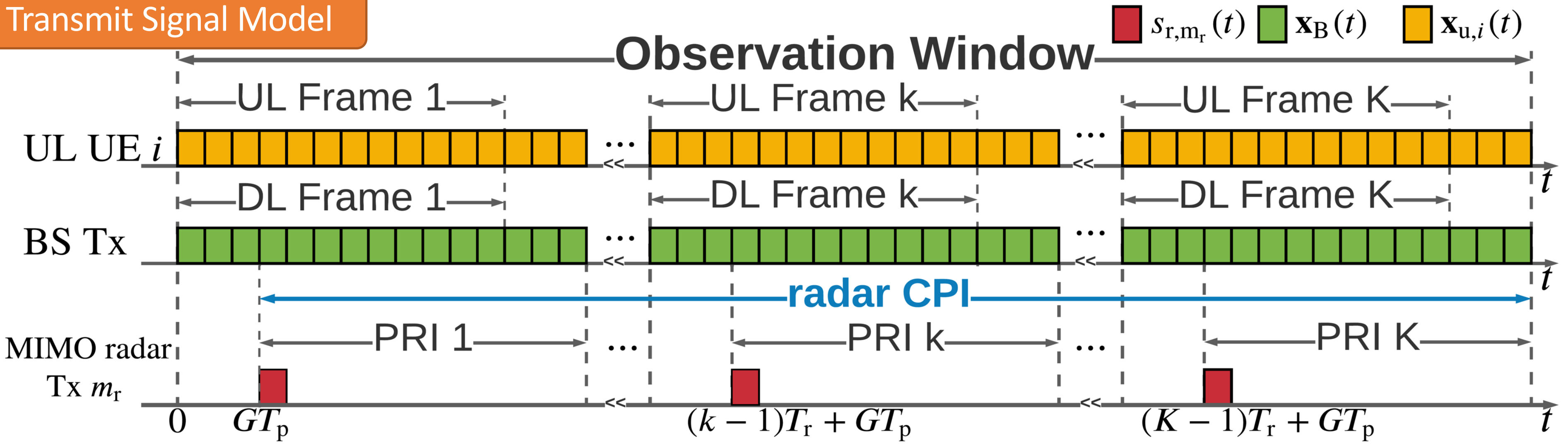
Compounded and weighted sum mutual information as metric

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

Precoder of UL UE i

Data stream of UL UE i

Transmit pulse shape filter

Radar Tx m_r:

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

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}:

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

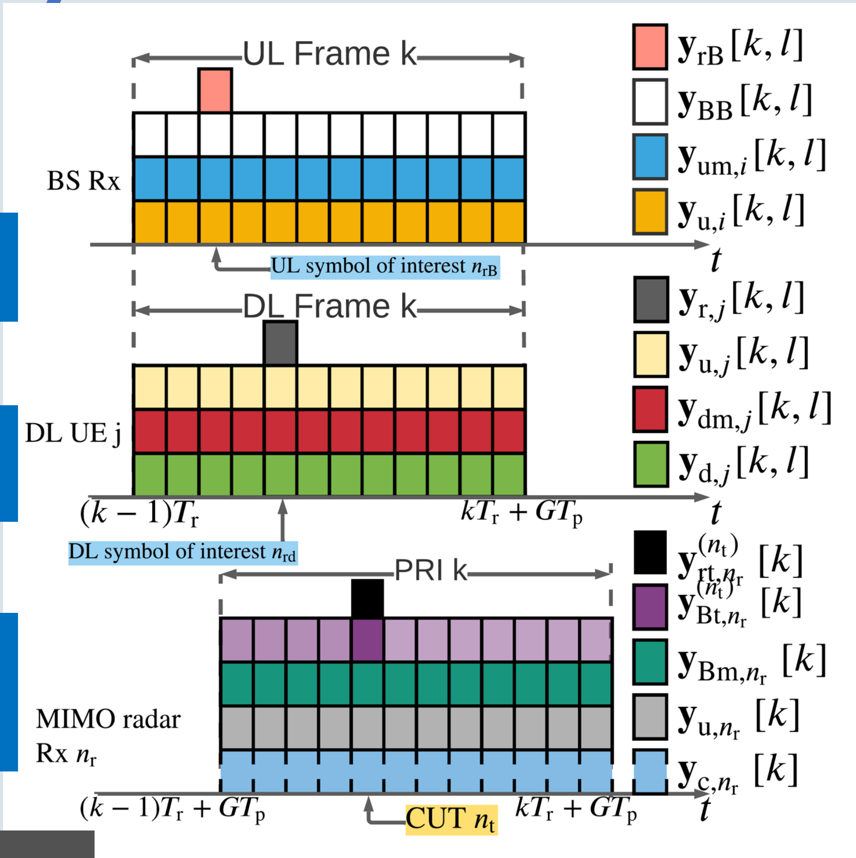
Target reflected DL signal

Multi-path propagated DL signal

UL signal

Clutter signal

Complex Gaussian Noise vectors



CWSM Maximization Problem

Receive Signal at n_r-th radar Rx:

$$I_{r,n_r} = \log \frac{det\left(\mathbf{U}_{\mathrm{r,n}_r}\left(\mathbf{R}_{\mathrm{s}} + \mathbf{R}_{\mathrm{in,n}_r}\right)\mathbf{U}_{\mathrm{r,n}_r}^{\dagger}\right)}{det\left(\mathbf{U}_{\mathrm{r,n}_r}\mathbf{R}_{\mathrm{in,n}_r}\mathbf{U}_{\mathrm{r,n}_r}^{\dagger}\right)}$$

Linear receiver at Radar Rx

Radar interference-plus-noise covariance matrix

Receive Signal at BS Rx to decode UL UE i:

$$I_{u,i}[k] = \log\det\left(\mathbf{I} + \mathbf{U}_{\mathrm{u},i}[k]\mathbf{R}_i^u[k]\mathbf{U}_{\mathrm{u},i}^{\dagger}[k]\left(\mathbf{U}_{\mathrm{u},i}[k]\mathbf{R}_{\mathrm{in},i}^{\mathrm{u}}[k]\mathbf{U}_{\mathrm{u},i}^{\dagger}[\boldsymbol{k}]\right)^{-1}\right)$$

Linear receiver at BS Rx to decode UL UE i

Receive Signal at BS Rx to decode DL UE j:

$$I_{d,j}[k] = \log\det\left(\mathbf{I} + \mathbf{U}_{\mathrm{d},j}[k]\mathbf{R}_j^{\mathrm{d}}[k]\mathbf{U}_{\mathrm{d},j}^{\dagger}[k]\left(\mathbf{U}_{\mathrm{d},j}[k]\mathbf{R}_{\mathrm{in},j}^{\mathrm{d}}[k]\mathbf{U}_{\mathrm{d},j}^{\dagger}[\boldsymbol{k}]\right)^{-1}\right)$$

Compounded and weighted sum mutual information (CWSM):

$$I_{\mathrm{CWSM}} = \sum_{n_r=1}^{N_r} \alpha_{n_r}^{r} I_{r,n_r} + \sum_{k=1}^{K}\sum_{i=1}^{I} \alpha_i^{\mathrm{u}} I_{u,i}[k] + \sum_{k=1}^{K}\sum_{j=1}^{J} \alpha_d^{\mathrm{j}} I_{d,j}[k]$$

Weight of radar Rx nr

Weight of UL UE i

CWSM Maximization Problem

$$\underset{\{\mathbf{P}\},\{\mathrm{U}\},\mathbf{A}}{\text{maximize}} \quad I_{\mathrm{CWSM}}\{\{\mathbf{P}\},\{\mathrm{U}\},\mathbf{A}\}$$

subject to

$$\left.\begin{array}{l} \sum_{j=1}^{J} \mathrm{tr}\left\{P_{d,j}[k]P_{d,j}^{\dagger}[k]\right\} \leq P_{\mathrm{B}}, \\ \mathrm{tr}\left\{P_{u,i}[k]P_{u,i}^{\dagger}[k]\right\} \leq P_{\mathrm{u}}, \end{array}\right\} \text{DL and UL Power budgets}$$

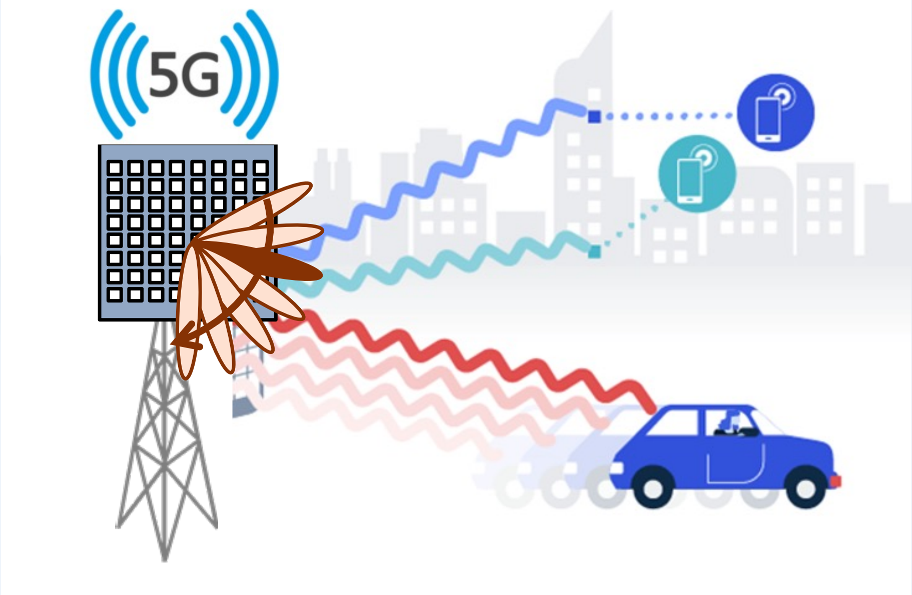
$$\left.\begin{array}{l} R_j^d[k] \geq R_{\mathrm{DL}}, \\ R_i^u[k] \geq R_{\mathrm{UL}}, \end{array}\right\} \text{QoS constraints}$$

$$\left.\begin{array}{l} \left\|a_{m_r}\right\|^2 = P_{\mathrm{r},m_r}, \\ \dfrac{K \max\limits_{k=1,\cdots,K} \left|\boldsymbol{a}_{m_r}[k]\right|^2}{P_{r,m_r}} \leq \gamma_{m_r}, \forall i,j,k,m_r \end{array}\right\} \text{PAR for radar codes}$$

Waveform code matrix
$\mathbf{A} = \left[\mathbf{a}^{\mathsf{T}}[1],\cdots,\mathbf{a}^{\mathsf{T}}[K]\right]$
$= \left[\boldsymbol{a}_1,\cdots,\boldsymbol{a}_{\mathrm{M_r}}\right]$

Non-convex problem solved through BCD algorithm

Courtesy: The Expanse (S06E05)



Distributed Algorithms

BCD-Based Iterative Alternating Algorithm

PAR constraint

- Partition the CWSM maximization problem into two sub problems
  1. Original problem w/o the PAR constraint
  2. : Matrix nearness problem to impose the PAR constraint

Cost function

- Equivalence of the weighted sum rate and the WMMSE
- Theorem 1

QoS constraints

- First order Taylor series expansions
- Theorem 2

BCD based Iterative Alternating Algorithm

$$\Sigma_{\text{wmse}}\{\{\mathbf{P}\},\{\mathbf{U}\},\mathbf{A}\} \triangleq \sum_{n_r=1}^{N_r} \alpha_{n_r}^{r} \mathrm{tr}\{\mathbf{W}_{r,n_r}[k]\mathbf{E}_{r,n_r}[k]\} + \sum_{k=1}^{K}\sum_{i=1}^{I} \alpha_i^{\mathrm{u}} \mathrm{tr}\{\mathbf{W}_{\mathrm{u},i}[k]\mathbf{E}_{\mathrm{u},i}[k]\} + \sum_{k=1}^{K}\sum_{j=1}^{J} \alpha_j^{\mathrm{d}} \mathrm{tr}\{\mathbf{W}_{\mathrm{d},j}[k]\mathbf{E}_{\mathrm{d},j}[k]\}$$

Weighted mean square error sum

Weight matrix

Mean square error matrix

Theorem (Liu, Mishra and Saquib, 2020)

Solving the problem

$$\begin{aligned} \underset{\{\mathbf{P}\},\{\mathrm{U}\},\mathbf{A}}{\text{minimize}} \quad & \Sigma_{\text{wmse}}\{\{\mathbf{P}\},\{\mathrm{U}\},\mathbf{A}\} \\ \text{subject to } & \textstyle\sum_{j=1}^{J} \mathrm{tr}\left\{P_{d,j}[k]P_{d,j}^{\dagger}[k]\right\} \le P_{\mathrm{B}}, \\ & \mathrm{tr}\{P_{u,i}[k]P_{u,i}^{\dagger}[k]\} \le P_{\mathrm{u}}, \\ & R_i^{u}[k] \ge R_{\mathrm{UL}}, \\ & R_j^{d}[k] \ge R_{\mathrm{DL}}, \end{aligned}$$

yields the exact solution of the original problem without the PAR constraint.

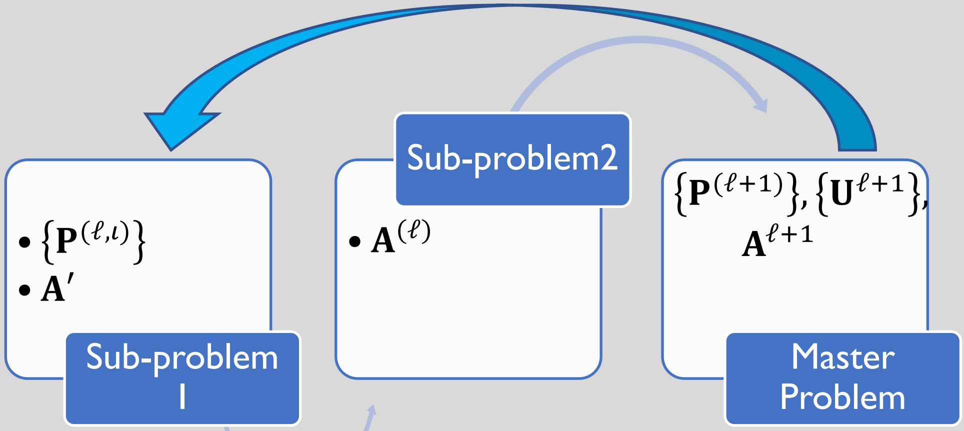
BCD based Iterative Alternating Algorithm

Sub-problem 2: Matrix nearness problem

$$\begin{aligned}
\underset{\boldsymbol{a}_{m_r},\forall m_r}{\text{maximize}} \quad & \left\|\boldsymbol{a}_{m_r} - \boldsymbol{a}'_{m_r}\right\|_2 \\
\text{Subject to} \quad & \left\|\boldsymbol{a}_{m_r}\right\|^2 = P_{\mathrm{r},m_r}, \\
& \frac{K \max\limits_{k=1,\cdots,K} \left|\boldsymbol{a}_{m_r}[k]\right|^2}{P_{r,m_r}} \le \gamma_{m_r}
\end{aligned}$$

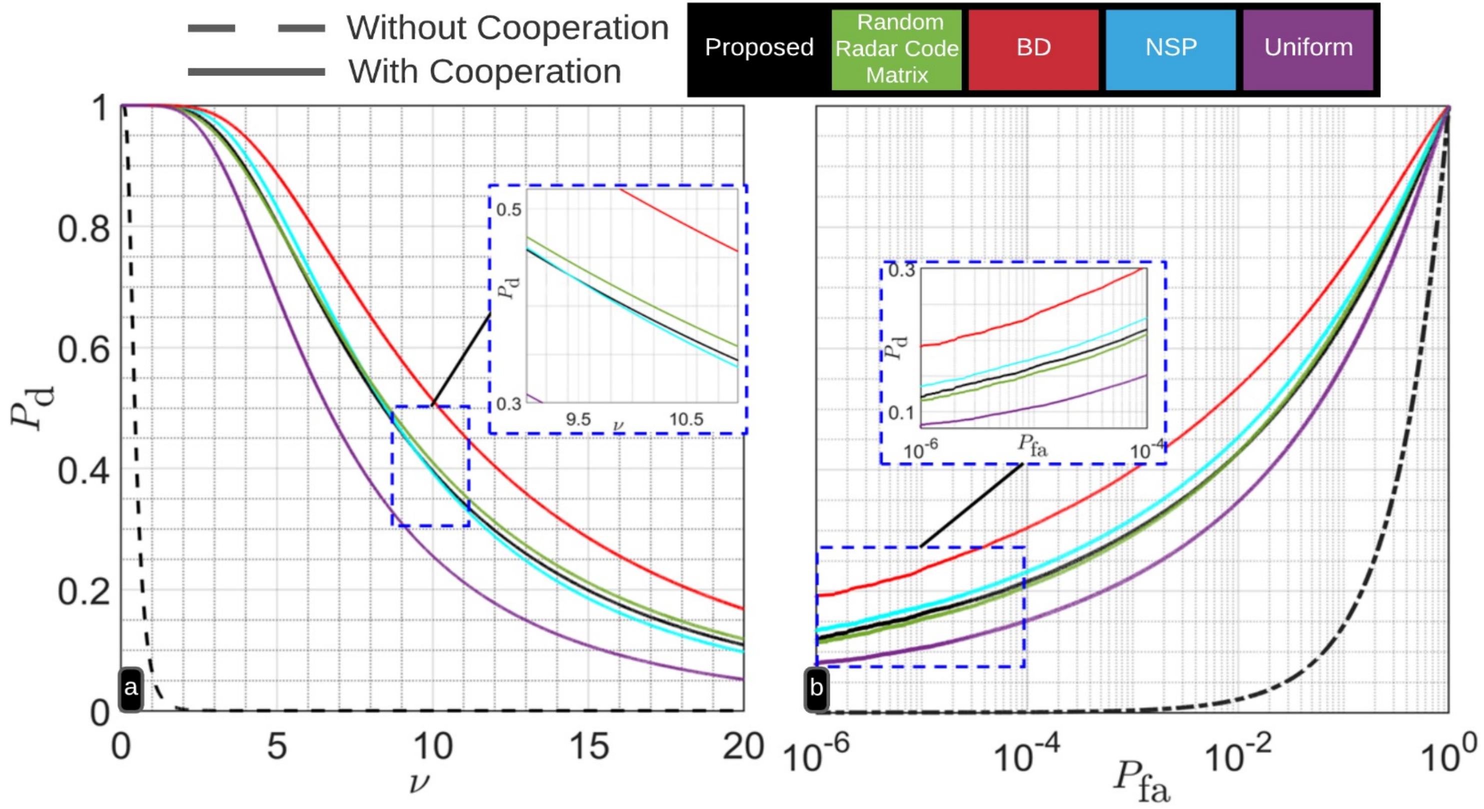
→ a structured tight frame design problem

BCD Iteration Summary

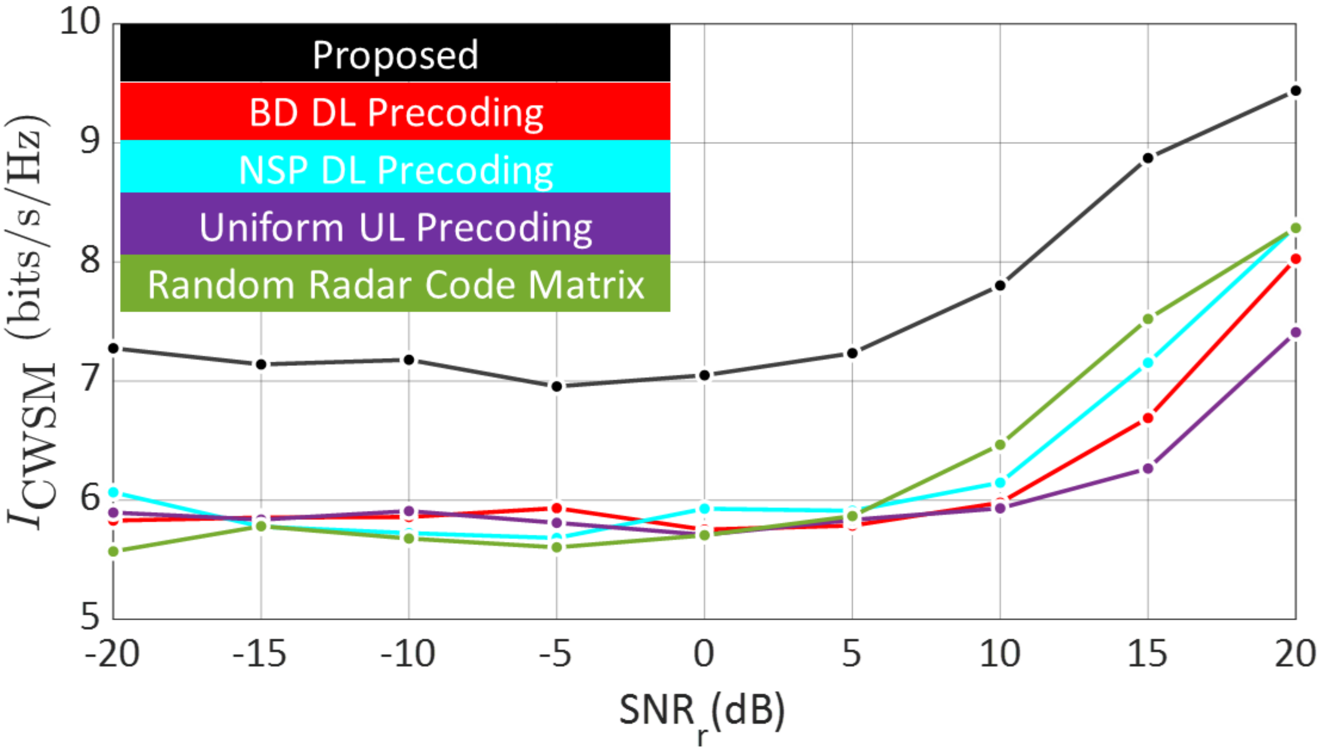


ℓ: iteration index of the master problem
ι: iteration index of the sub-problem 2

Numerical Experiments



Numerical Experiments

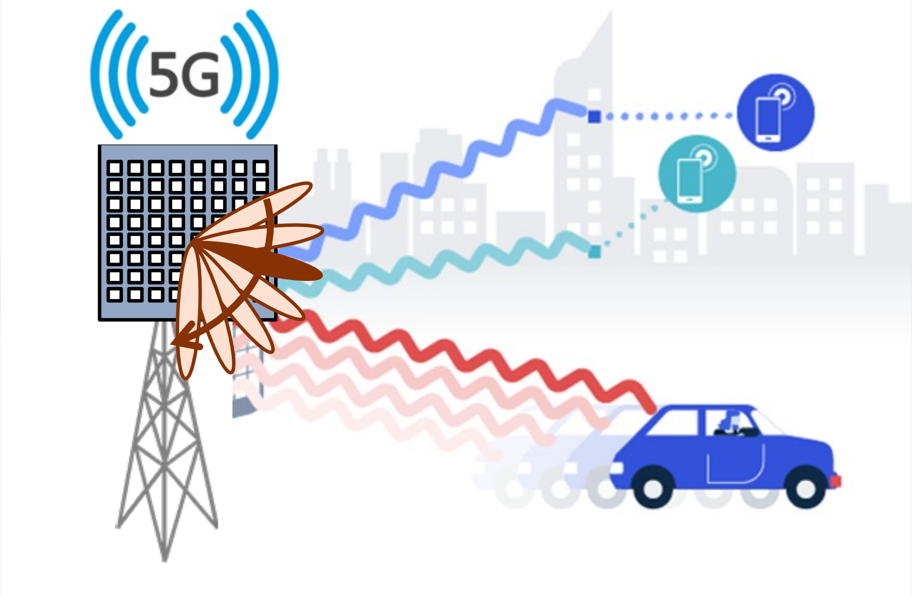


The proposed precoder design scheme outperforms some conventional strategies

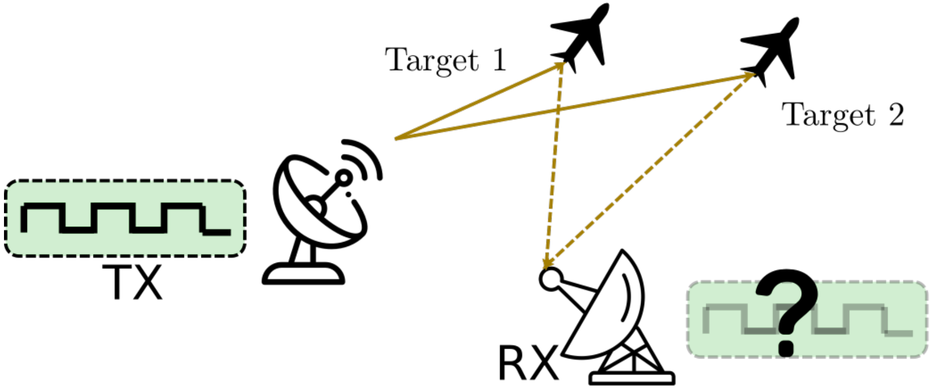
J. Liu, K. V. Mishra and M. Saquib, “Co-Designing Statistical MIMO Radar and In-band Full-Duplex Multi-User MIMO Communications," arxiv preprint 2020.

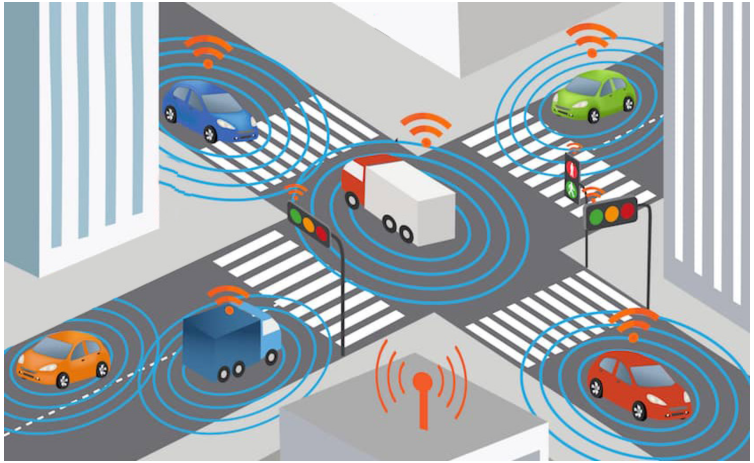
Courtesy: Species II

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 $\boldsymbol{s}, \boldsymbol{g}$

System Model

Assumptions

- The channel parameters are normalized continuous-valued. $\boldsymbol{\tau_r}, \boldsymbol{\nu_r}, \boldsymbol{\alpha_r}, \boldsymbol{\tau_c}, \boldsymbol{\nu_c}, \boldsymbol{\alpha_c} \in [\mathbf{0}, \mathbf{1}]$
- The transmitted signals lies in a low dimensional subspace (J<<M (lifting trick)

$$\boldsymbol{s} = \boldsymbol{B}\boldsymbol{u} \rightarrow \boldsymbol{B} \in \mathbb{C}^{M\times J}, \boldsymbol{u} \in \mathbb{C}^{J} \mid \boldsymbol{g} = \boldsymbol{D}\boldsymbol{v} \rightarrow \boldsymbol{B} \in \mathbb{C}^{MP\times PJ}, \boldsymbol{u} \in \mathbb{C}^{PJ}$$

- The channels are sparse $L, Q << MP$

Linear Sensing Model

- The discrete signal model with the lifting trick can be written as follows

$$\boldsymbol{y} = \aleph_r(\boldsymbol{Z}_r) + \aleph_c(\boldsymbol{Z}_c)$$

Where $\aleph_r$ and $\aleph_c$ are linear operator

- $\mathbf{Z}_\mathrm{r}$ and $\mathbf{Z}_\mathrm{c}$ are rank-one matrices containing all the unknown variables, defined as:

$$\boldsymbol{Z}_r = \sum_{\ell=0}^{L-1} [\alpha_r]_\ell \boldsymbol{a}(\boldsymbol{r}_\ell)\boldsymbol{u}^H, \boldsymbol{Z}_c = \sum_{q=0}^{Q-1} [\alpha_c]_q \boldsymbol{a}(\boldsymbol{c}_q)\boldsymbol{v}^H$$

where $a(\boldsymbol{r}) = a([\tau, v]) = [e^{(-j2\pi(-N\tau,(0)v)}, \dots, e^{(-j2\pi(-N\tau,(0)v)}, \dots, e^{(-j2\pi(N\tau,(P-1)v)}]$

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.

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

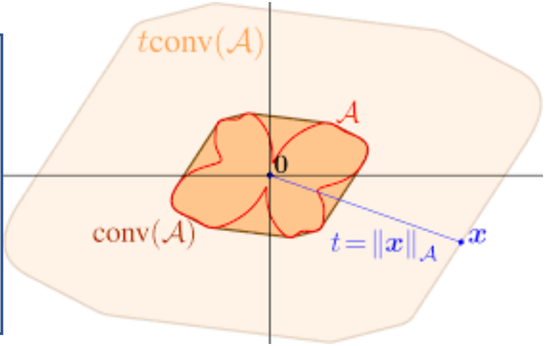
$$\mathcal{A}_r = \left\{\boldsymbol{u}\boldsymbol{a}(\boldsymbol{r})^H : \boldsymbol{r} \in [0,1)^2, ||\boldsymbol{u}||_2 = 1\right\}$$
$$\mathcal{A}_c = \left\{\boldsymbol{v}\boldsymbol{a}(\boldsymbol{c})^H : \boldsymbol{c} \in [0,1)^2, ||\boldsymbol{v}||_2 = 1\right\}$$

- 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.

Dual problem and SDP formulation

- The dual optimization problem allows to locate the off-the-grid parameters via positive trigonometric polynomials.
- The dual optimization problem is given by

Dual variable   Dual atomic norms

$$\underset{q}{\text{maximize}}\langle \boldsymbol{q}, \boldsymbol{y}\rangle_{\mathbb{R}} \text{ subject to } \left\|\aleph_r^*(\boldsymbol{q})\right\|_{\mathcal{A}_r}^* \leq 1, \left\|\aleph_c^*(\boldsymbol{q})\right\|_{\mathcal{A}_c}^* \leq 1$$

- The dual problem can be casted to a SDP problem via the Bounded Real Lemma

Gram matrix

$$\underset{q,Q}{\text{maximize}}\langle q, y\rangle_{\mathbb{R}} \text{ subject to } \begin{bmatrix} \boldsymbol{Q} & \widetilde{\boldsymbol{Q}}_r^H \\ \widetilde{\boldsymbol{Q}}_r & \boldsymbol{I}_J \end{bmatrix} \succcurlyeq \mathbf{0}, \begin{bmatrix} \boldsymbol{Q} & \widetilde{\boldsymbol{Q}}_c^H \\ \widetilde{\boldsymbol{Q}}_c & \boldsymbol{I}_{PJ} \end{bmatrix} \succcurlyeq \mathbf{0}, \mathbf{Tr}(\boldsymbol{\Theta}_n \otimes \mathbf{Q}) = \boldsymbol{\delta}_n$$

- Trigonometric Polynomials

$$\boldsymbol{f}_r(\boldsymbol{r}) = \widetilde{\boldsymbol{Q}}_r \boldsymbol{a}(\boldsymbol{r}) \in \mathbb{R}^J \mid \boldsymbol{f}_c(\boldsymbol{c}) = \widetilde{\boldsymbol{Q}}_c \boldsymbol{a}(\boldsymbol{c}) \in \mathbb{R}^{PJ}$$

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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 certificate and recovery guarantee

Proposition (Vargas, Mishra, Jacome, Sadler, Arguello 2022)

Let $\mathcal{R} = \{r_\ell\}_{\{\ell=0\}}^{\{L-1\}}$ and $C = \{c_q\}_{\{q=0\}}^{\{Q-1\}}$, $\hat{\mathbf{Z}}_\mathbf{r}$, $\hat{\mathbf{Z}}_\mathbf{c}$ is the unique solution if

$$\left|\left|f_r(r)\right|\right| = 1,\ r \in \mathcal{R}, \left|\left|f_r(r)\right|\right| < 1,\ r \in [0,1]^2 \backslash \mathcal{R}$$

$$\left|\left|f_c(c)\right|\right| = 1, c \in \mathcal{C}, \left|\left|f_c(c)\right|\right| < 1, c \in [0,1]^2 \backslash \mathcal{C}$$

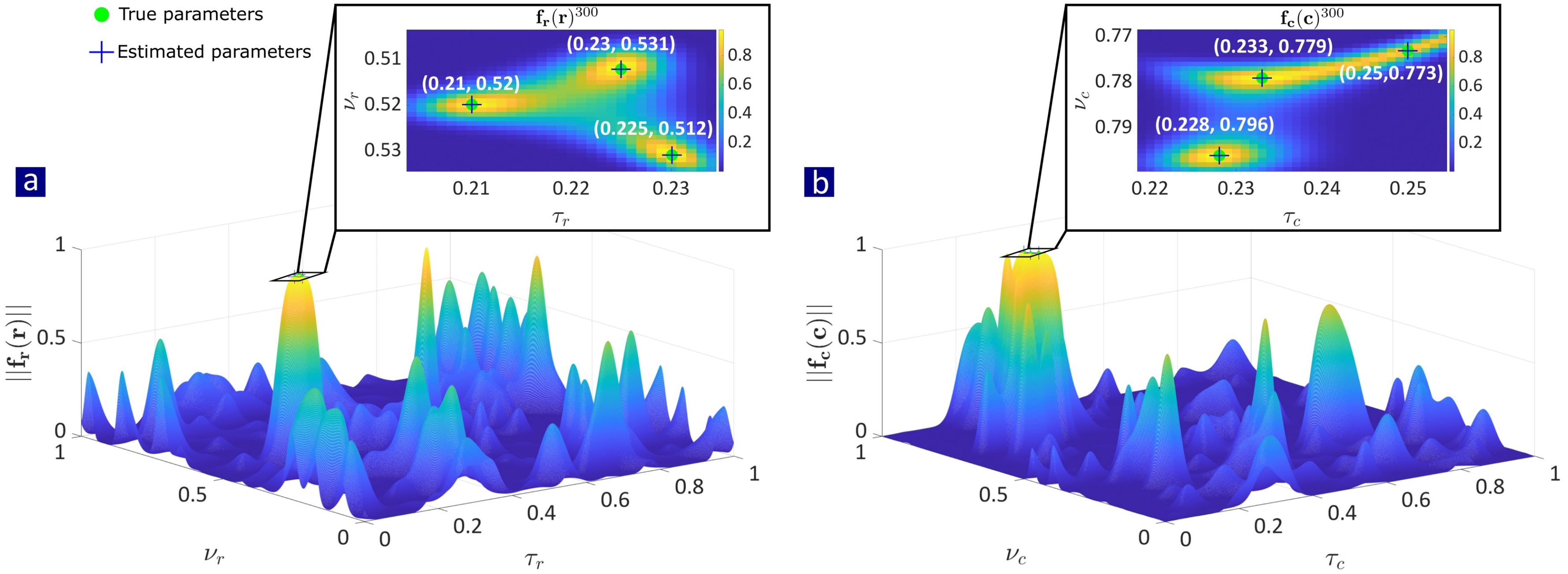
Theorem (Vargas, Mishra, Jacome, Sadler, Arguello 2022)

We can recover $\mathbf{Z}_\mathrm{r}$ and $\mathbf{Z}_\mathrm{c}$ precisely with a probability of $1 - \delta$ given by

$$MP \geq CJ\mu \max\,(L, Q) \log^2\left(\frac{MPJ}{\delta}\right) \max\left(\log\left(\frac{MPLJ}{\delta}\right), \log\left(\frac{MPQJ}{\delta}\right)\right)$$

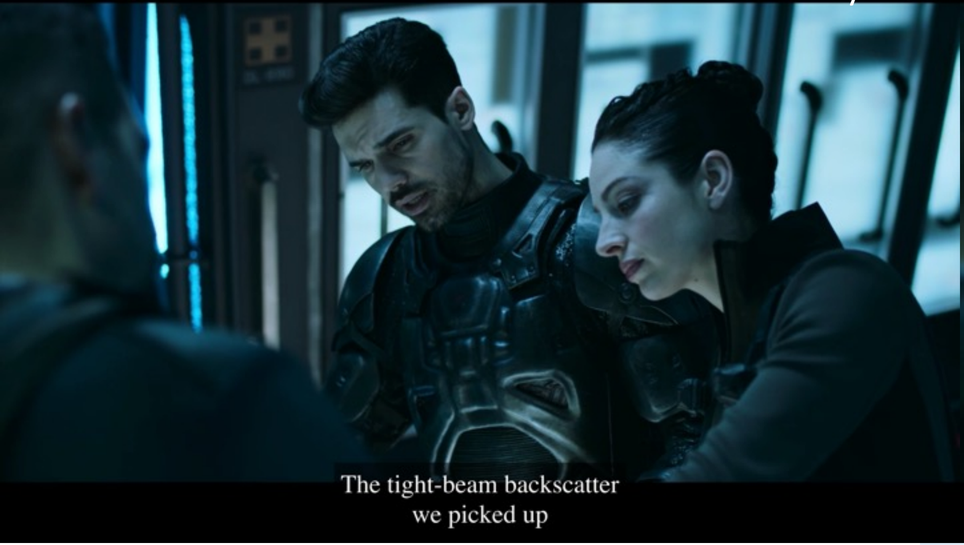
E. Vargas, K. V. Mishra, R. Jacome, B. M. Sadler and H. Arguello, “Dual-Blind Deconvolution for Overlaid Radar-Communications Systems,” arXiv preprint arXiv:2208.04381, 2022.
E. Vargas, K. V. Mishra, R. Jacome, B. M. Sadler and H. Arguello, “Joint radar-communications processing from a dual-blind deconvolution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

Localization for single Rx

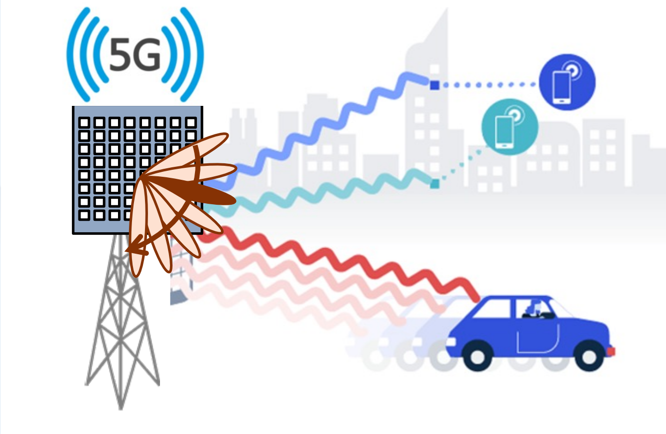


E. Vargas, K. V. Mishra, R. Jacome, B. M. Sadler and H. Arguello, "Dual-Blind Deconvolution for Overlaid Radar-Communications Systems," arXiv preprint arXiv:2208.04381, 2022.
E. Vargas, K. V. Mishra, R. Jacome, B. M. Sadler and H. Arguello, "Joint radar-communications processing from a dual-blind deconvolution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

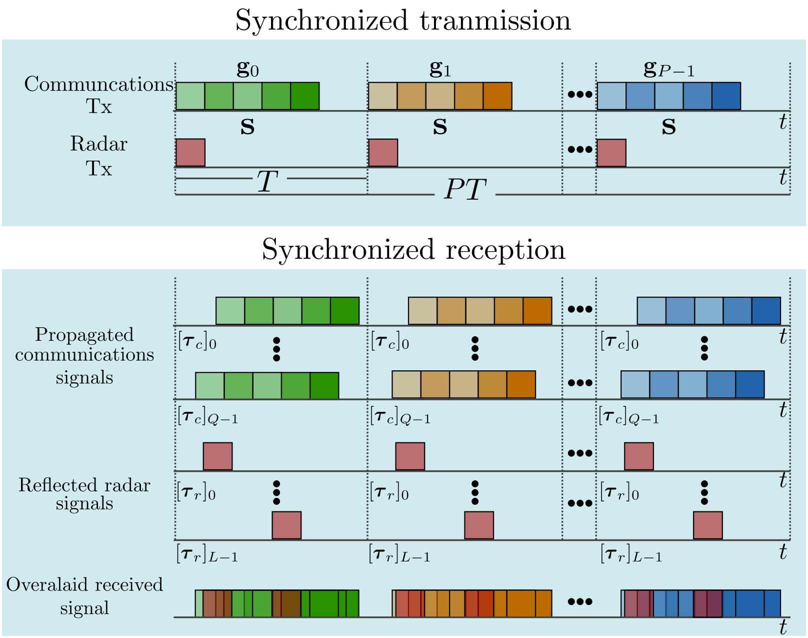
Courtesy: The Expanse (Season 5)

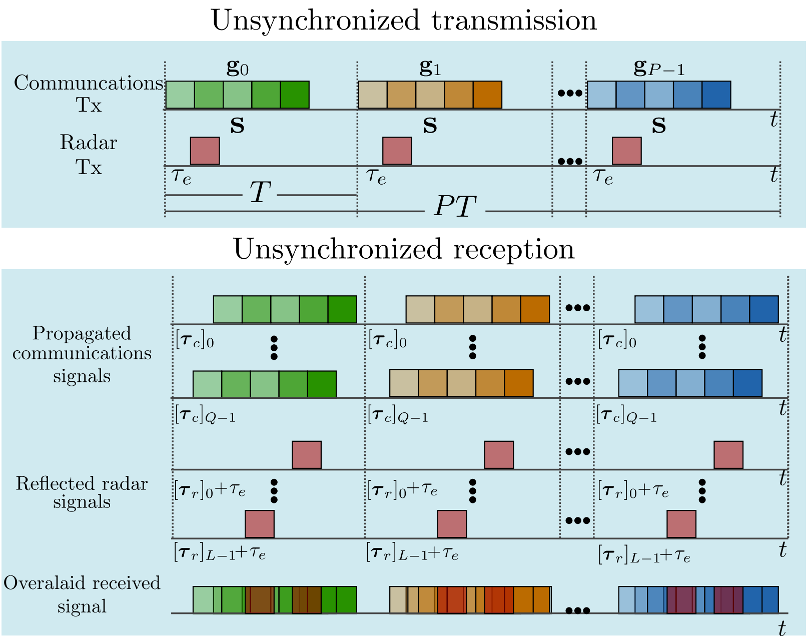


Practical Issues with DBD



Practical Issues: Lack of Synchronized transmission





- Rx signal

$$\|\boldsymbol{E}\|_2 < \mathrm{C_e}$$

$$E = \mathrm{diag}\left(\mathbf{1}_{P,1} \otimes \tilde{\boldsymbol{e}}(\boldsymbol{\tau_s})\right),$$

$$\tilde{\boldsymbol{e}}(\boldsymbol{\tau_s}) = [e^{j2\pi\tau_s(-N)}, \ldots, e^{j2\pi\tau_s(N)}]$$

$$[y]_{\tilde{n}} = \boldsymbol{h}_r^H \boldsymbol{E} \boldsymbol{e}_{\tilde{n}} \boldsymbol{b}_n^H \boldsymbol{u} + \boldsymbol{h}_c^H \boldsymbol{e}_{\tilde{n}} \boldsymbol{d}_{\tilde{n}}^H \boldsymbol{v}$$

- SDP formulation

$$\underset{\boldsymbol{q},\boldsymbol{Q}}{\text{minimize}} \ \|\boldsymbol{q} - \boldsymbol{y}\| \text{ subject to}$$

$$\begin{bmatrix} \boldsymbol{Q} & \tilde{\boldsymbol{Q}}_r^H \\ \tilde{\boldsymbol{Q}}_r & \rho^2 \boldsymbol{I}_J \end{bmatrix} \succcurlyeq \mathbf{0}, \begin{bmatrix} \boldsymbol{Q} & \tilde{\boldsymbol{Q}}_c^H \\ \tilde{\boldsymbol{Q}}_c & \mu_c \boldsymbol{I}_{PJ} \end{bmatrix} \succcurlyeq \mathbf{0},$$

$$\mathrm{Tr}(\boldsymbol{\Theta}_n \mathbf{Q}) = 0$$

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.
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Practical Issues

Multiple emitters

- Rx signal

$$\boldsymbol{y} = \sum_{l=1}^{K_r} \aleph_{r_l}(\boldsymbol{Z}_{r_l}) + \sum_{l=1}^{K_c} \aleph_{c_l}(\boldsymbol{Z}_{c_l})$$

- SDP formulation

$$\underset{q,Q}{\text{maximize}} < \mathbf{q}, \mathbf{y} >_{\mathbb{R}} \text{ subject to}$$

$$\begin{bmatrix} \boldsymbol{Q} & \widetilde{\boldsymbol{Q}}_{r_1}^H \\ \widetilde{\boldsymbol{Q}}_{r_1} & \boldsymbol{I}_J \end{bmatrix} \succcurlyeq \mathbf{0}, \begin{bmatrix} \boldsymbol{Q} & \widetilde{\boldsymbol{Q}}_{c_1}^H \\ \widetilde{\boldsymbol{Q}}_{c_1} & \mu_c \boldsymbol{I}_{PJ} \end{bmatrix} \succcurlyeq \mathbf{0},$$

$$\vdots$$

$$\begin{bmatrix} \boldsymbol{Q} & \widetilde{\boldsymbol{Q}}_{r_{K_r}}^H \\ \widetilde{\boldsymbol{Q}}_{r_{K_r}} & \boldsymbol{I}_J \end{bmatrix} \succcurlyeq \mathbf{0}, \begin{bmatrix} \boldsymbol{Q} & \widetilde{\boldsymbol{Q}}_{c_{K\_c}}^H \\ \widetilde{\boldsymbol{Q}}_{c_{K_c}} & \mu_c \boldsymbol{I}_{PJ} \end{bmatrix} \succcurlyeq \mathbf{0}$$

$$\mathrm{Tr}(\mathbf{\Theta}_{\mathbf{n}} \mathbf{Q}) = 0$$

Noisy measurements

- Rx signal

$$\boldsymbol{y} = \aleph_r(\boldsymbol{Z}_r) + \aleph_c(\boldsymbol{Z}_c) + \boldsymbol{\omega}$$
$$\|\boldsymbol{\omega}\|_2 < \mu$$

- SDP formulation

$$\underset{q,Q}{\text{maximize}} \langle q, y \rangle_{\mathbb{R}} - \mu \|\boldsymbol{q}\|_2^2$$

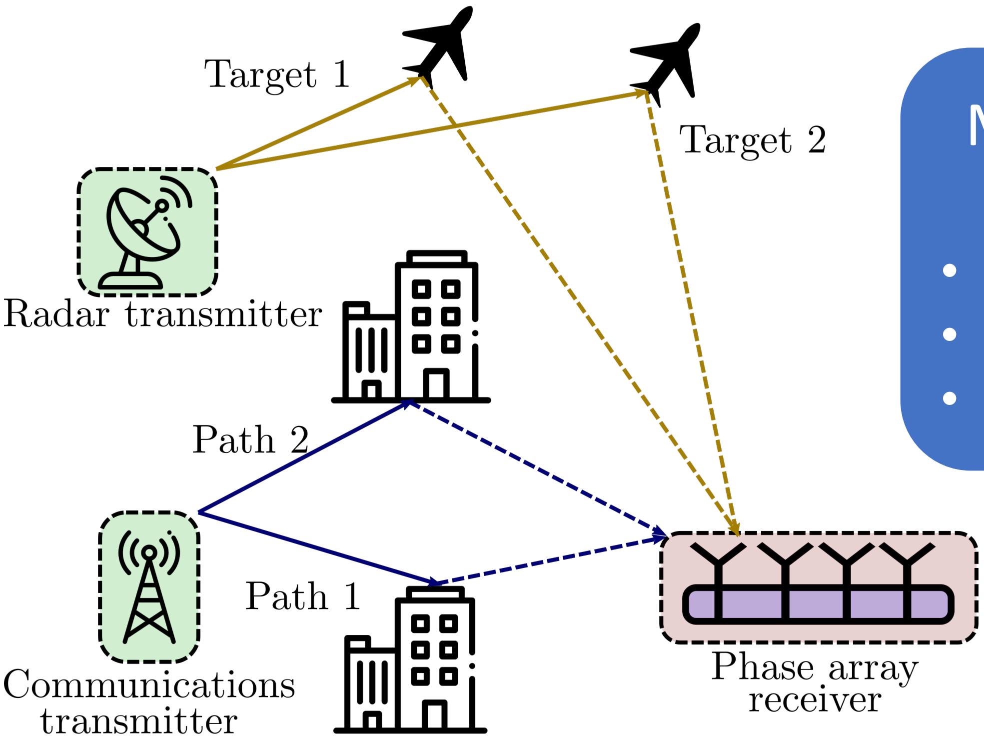
$$\text{subject to}$$

$$\begin{bmatrix} \boldsymbol{Q} & \widetilde{\boldsymbol{Q}}_r^H \\ \widetilde{\boldsymbol{Q}}_r & \boldsymbol{I}_J \end{bmatrix} \succcurlyeq \mathbf{0},$$

$$\begin{bmatrix} \boldsymbol{Q} & \widetilde{\boldsymbol{Q}}_c^H \\ \widetilde{\boldsymbol{Q}}_c & \boldsymbol{I}_{PJ} \end{bmatrix} \succcurlyeq \mathbf{0},$$

$$\mathbf{Tr}(\Theta_n \otimes \mathbf{Q}) = \boldsymbol{\delta}_{\boldsymbol{n}}$$

Multi-Antenna Co-existence

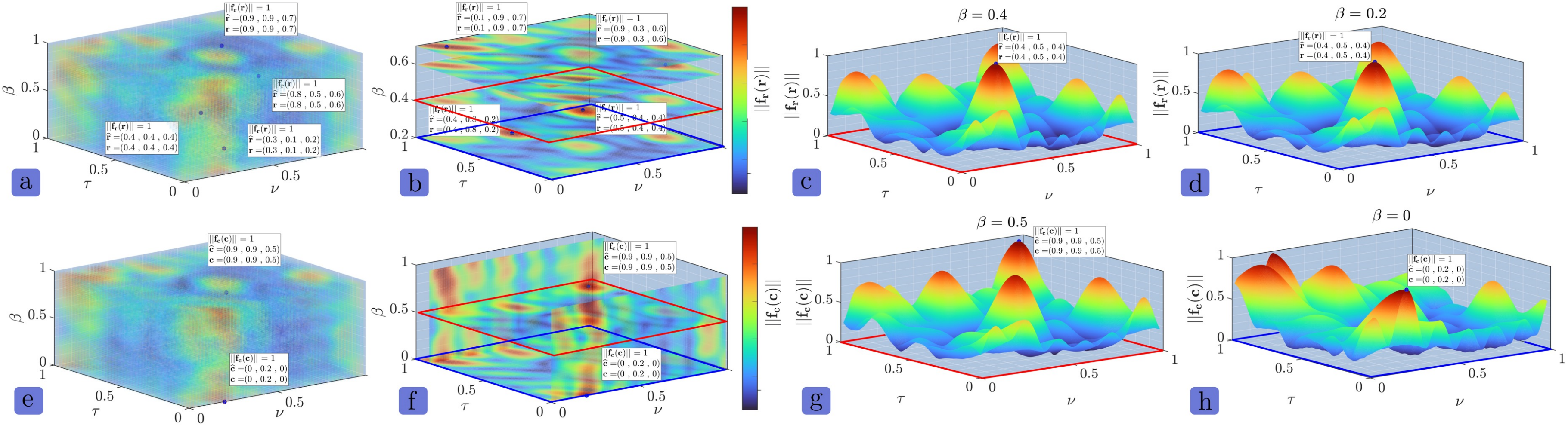


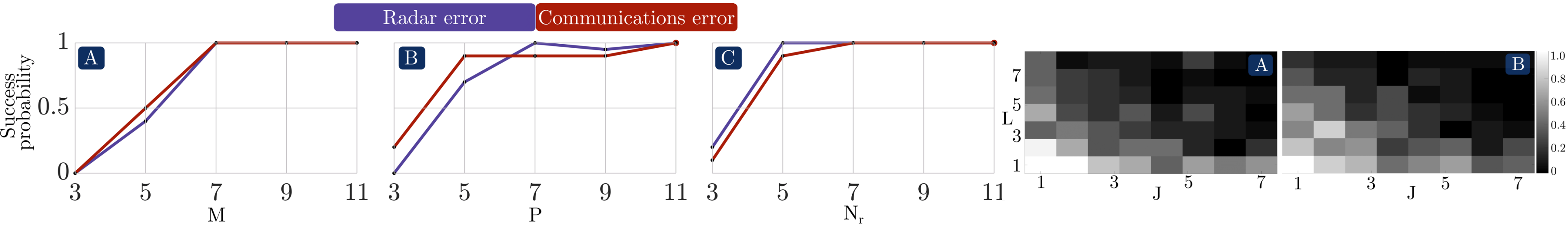
Multi-antenna Rx to estimate

- Time delay
- Doppler velocity
- Direction of arrival (DoA)

R. Jacome, K. V. Mishra, E. Vargas, B. M. Sadler and H. Arguello, "Multi-dimensional dual-blind deconvolution approach toward joint radar-communications," IEEE SPAWC, 2022.

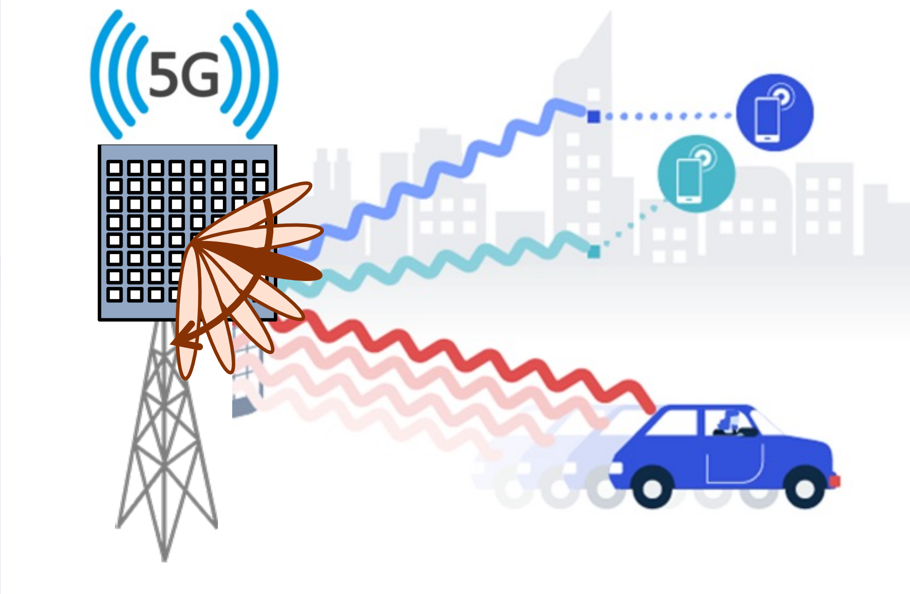
Numerical Experiments





R. Jacome, K. V. Mishra, E. Vargas, B. M. Sadler and H. Arguello, "Multi-dimensional dual-blind deconvolution approach toward joint radar-communications," IEEE SPAWC, 2022.

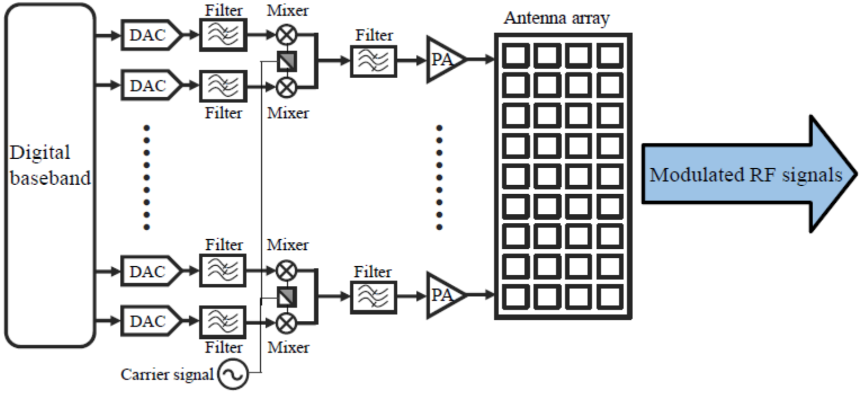
IRS-Aided ISAC



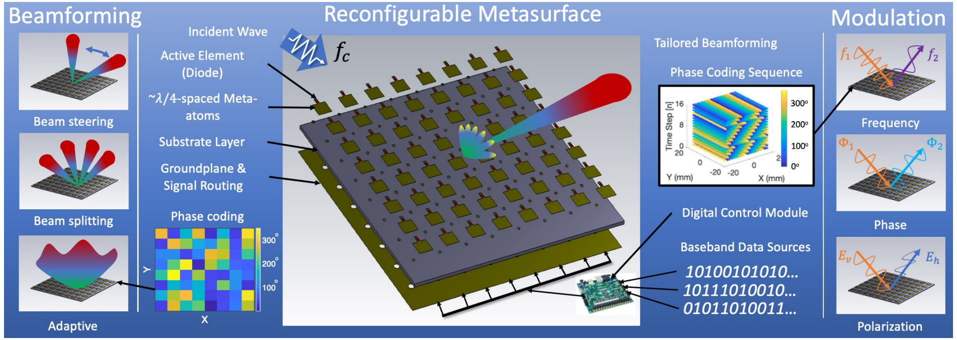
IRS-Based JRC

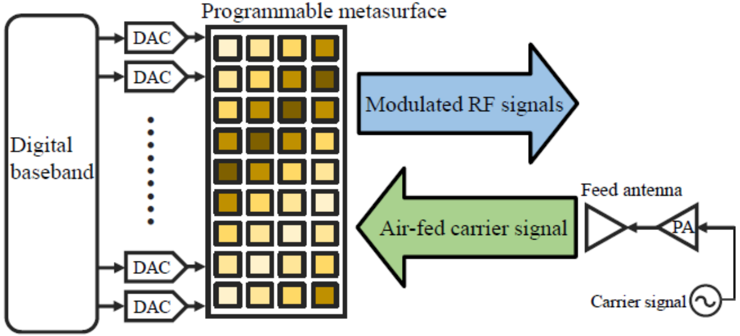
Intelligent Reflecting Surfaces

- Enhance capabilities in sensing/comms
- Simpler, lighter radar & comms payloads
- Reduce cost & amount of hardware in systems
- Potential wide-scale deployment of dynamic ISAC



(a)





J. A. Hodge, K. V. Mishra, and A. I. Zaghloul, “Deep inverse design of reconfigurable metasurfaces for future communications,” arxiv preprint 2021.

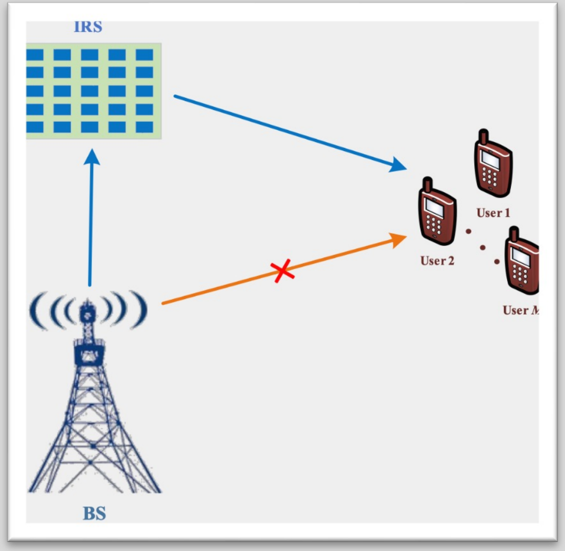
Ahmet M. Elbir, K. V. Mishra, M. R. B. Shankar and S. Chatzinotas, “The Rise of Intelligent Reflecting Surfaces in Integrated Sensing and Communications Paradigms,” 2021.

Tong Wei, L. Wu. K. V. Mishra, M. R. B. Shankar and B. Ottersten,” Multi-IRS-Aided Wideband Integrated Sensing and Communications,” 2021

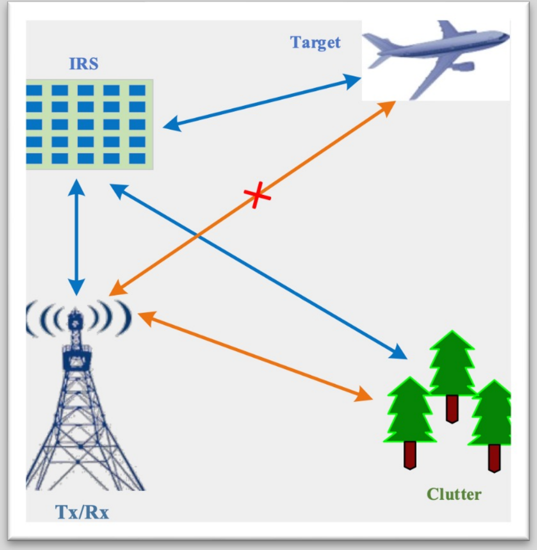
Intelligent Reflecting Surfaces (IRS)

- Meta surface consists of massive near-passive elements
  - Each element can change the phase of impinging signals
- Beamforming for the direction of user or target
- Flexible deployment (on the buildings or walls)

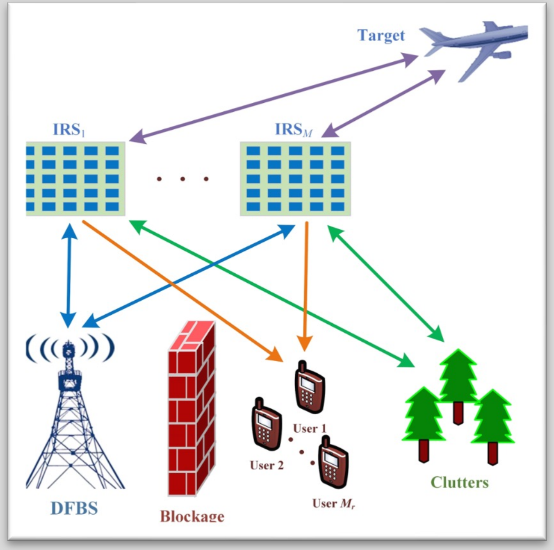
- Increased signal strength in LoS
- Enabling service to NLoS
- Nearly passive



IRS-aided communications system

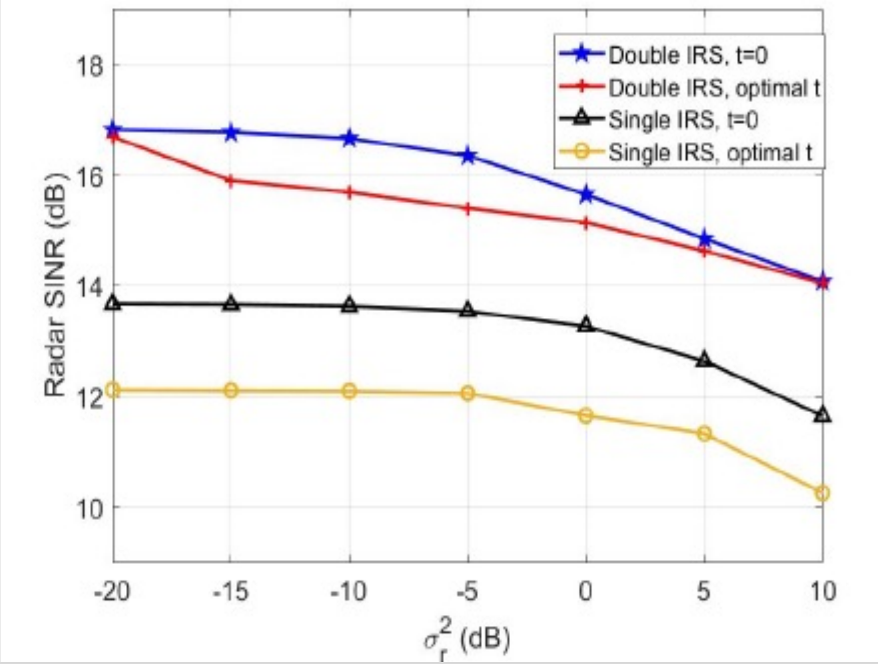


IRS-aided radar system

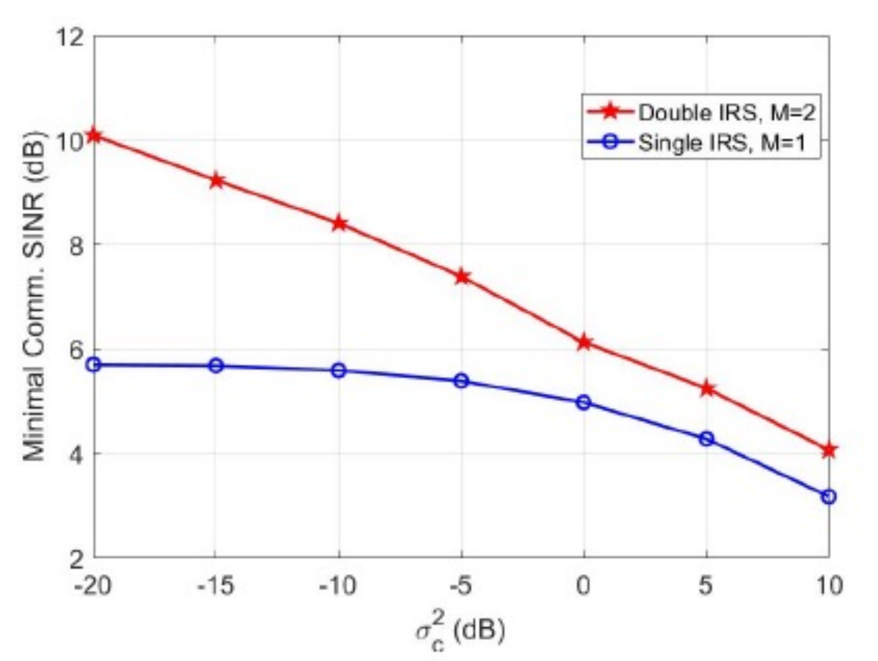


Multi-IRS JRC/ DFRC System

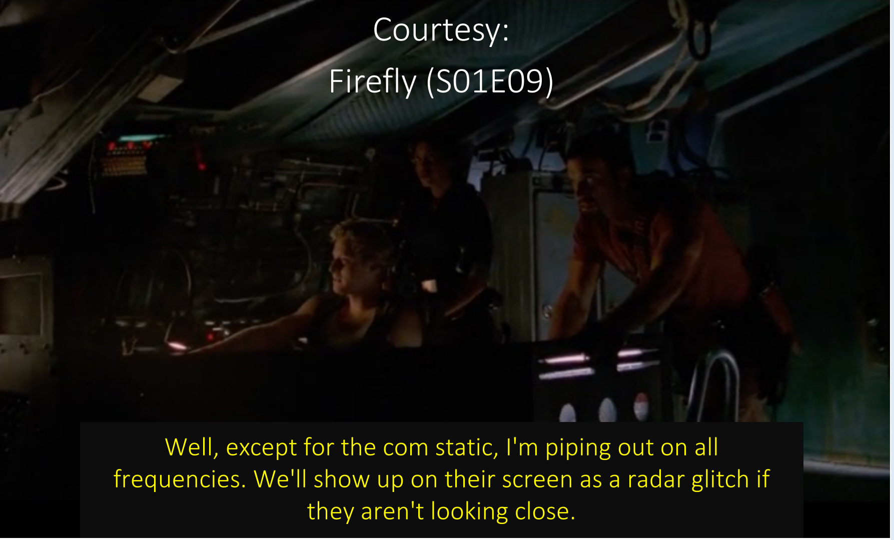
Representative Results



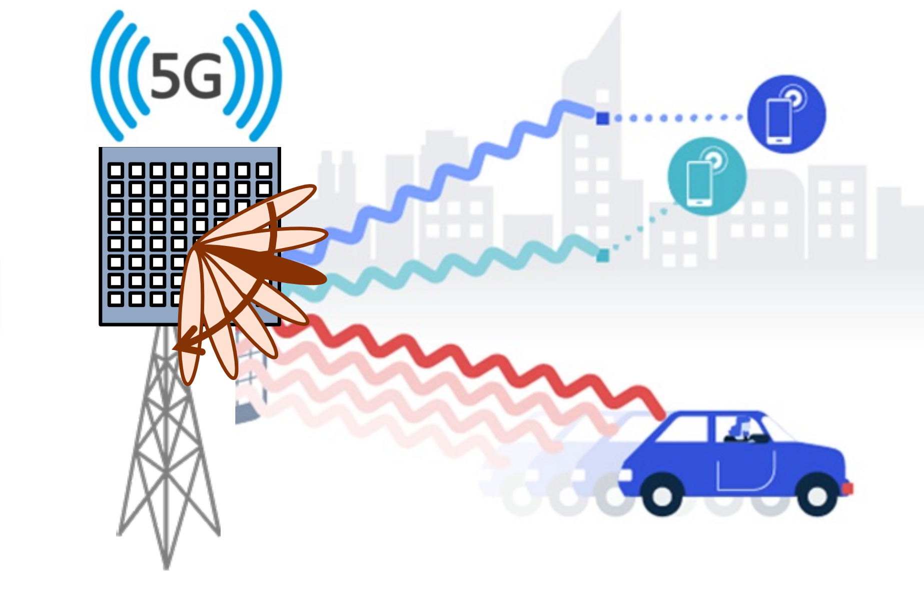
Radar SINR v/s Noise Power



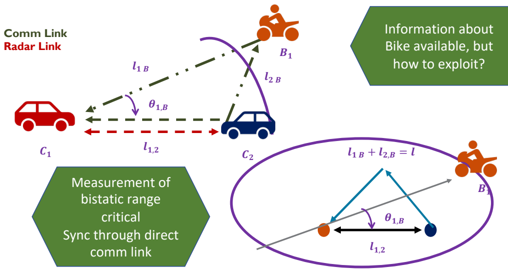
Min Comm SINR v/s Noise Power



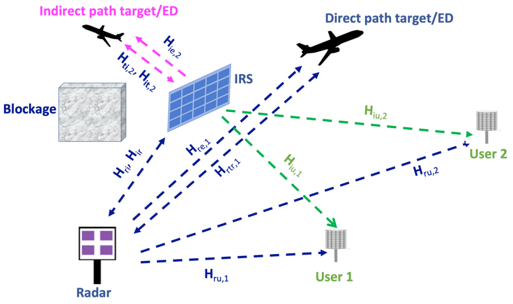
Other Distributed ISAC Architectures



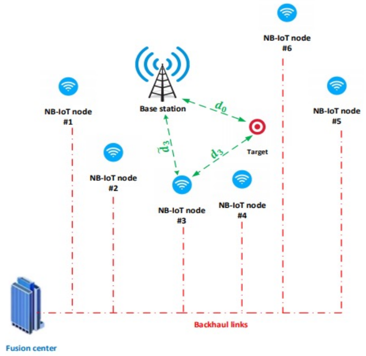
Emerging Distributed JRC/ISAC Trends



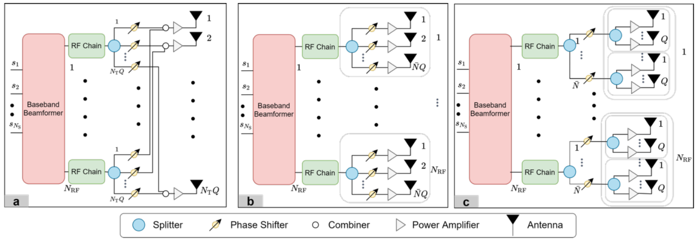
Sensor Fusion



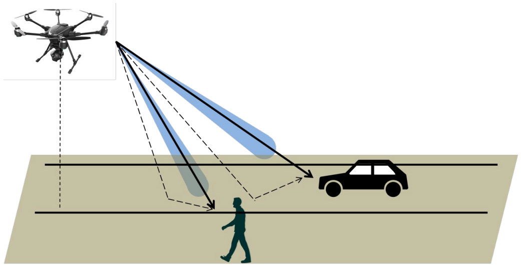
Secure IRS-Aided DFRC



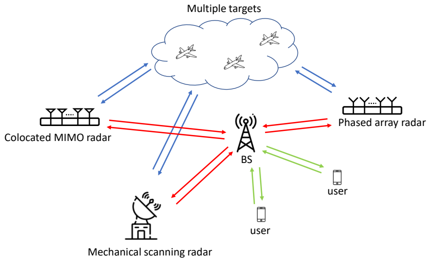
Passive ISAC



THz JRC



Drone-Borne ISAC



Heterogenous ISAC

S. H. Dokhanchi, M. R. B. Shankar, K. V. Mishra, and B. Ottersten, "Enhanced Automotive Target Detection through Radar and Communications Sensor Fusion," IEEE ICASSP 2021.

S. Sedighi, K. V. Mishra, M. R. B. Shankar and B. Ottersten, "Localization With One-Bit Passive Radars in Narrowband Internet-of-Things Using Multivariate Polynomial Optimization," IEEE T-SP, 2021.

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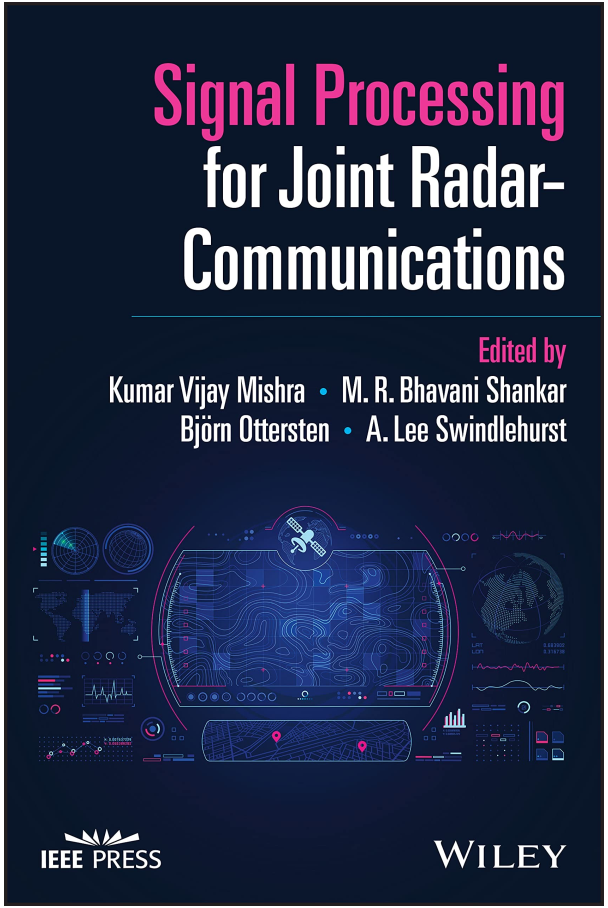
S. S. Ram and K. V. Mishra, "UAV-Based Urban Monitoring Using on-Board 802.11 ad Radar," IEEE SAM 2022.

L. Wu, K. V. Mishra, M. R. B. Shankar and B. Ottersten, "Heterogeneously-Distributed Joint Radar Communications: Bayesian Resource Allocation," IEEE J-SAC, 2022.

Tong Wei, L. Wu. K. V. Mishra, M. R. B. Shankar and B. Ottersten," Multi-IRS-Aided Wideband Integrated Sensing and Communications," 2022.

Thank you!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Edited by
Kumar Vijay Mishra • M. R. Bhavani Shankar
Björn Ottersten • A. Lee Swindlehurst
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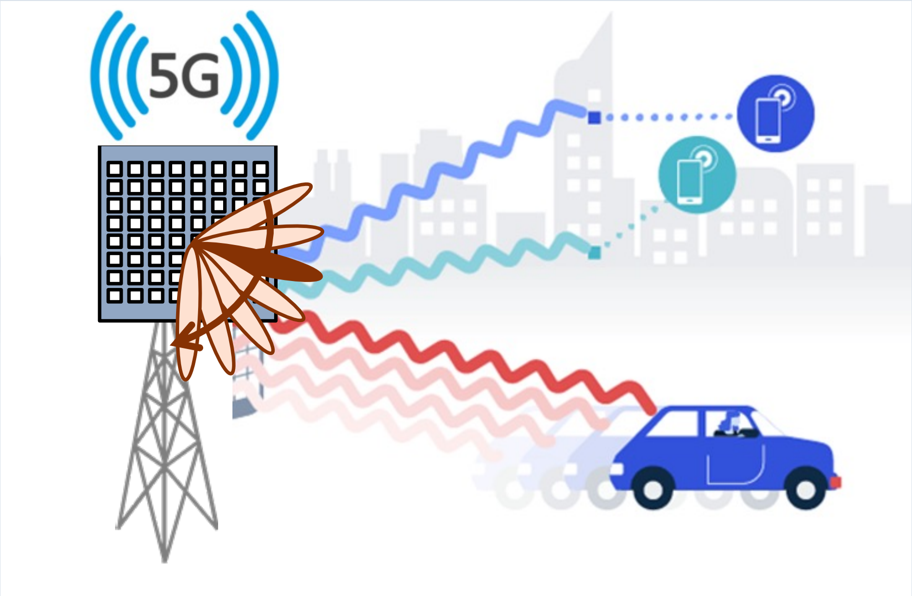
5G