Full-Duplex Distributed Integrated Sensing and Communications

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United States DEVCOM Army Research Laboratory

IEEE Future Networks Initiative Distinguished Lecture

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Courtesy: For All Mankind (S02E01)

Solar flare that size,
there's a good chance

we're gonna have interference
across the broadcast spectrum.

Let's alert the FCC
and get them ready for that.

Acknowledgements

- Prof. Mohammad Saquib, U of Texas at Dallas
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- Prof. Bjorn Ottersten, U of Luxembourg
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DEVCOM
ARMY RESEARCH
LABORATORY

The National Academies of
SCIENCES
ENGINEERING
MEDICINE

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Radar Spectrum Allocation

Modern radar systems 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/802.11 ah/f	WiMAX, JTIDS	LTE	802.11a/ac	LTE	802.11ad, mmwave comm

DARPA

Shared Spectrum Access for Radar and Communications (SSPARC)

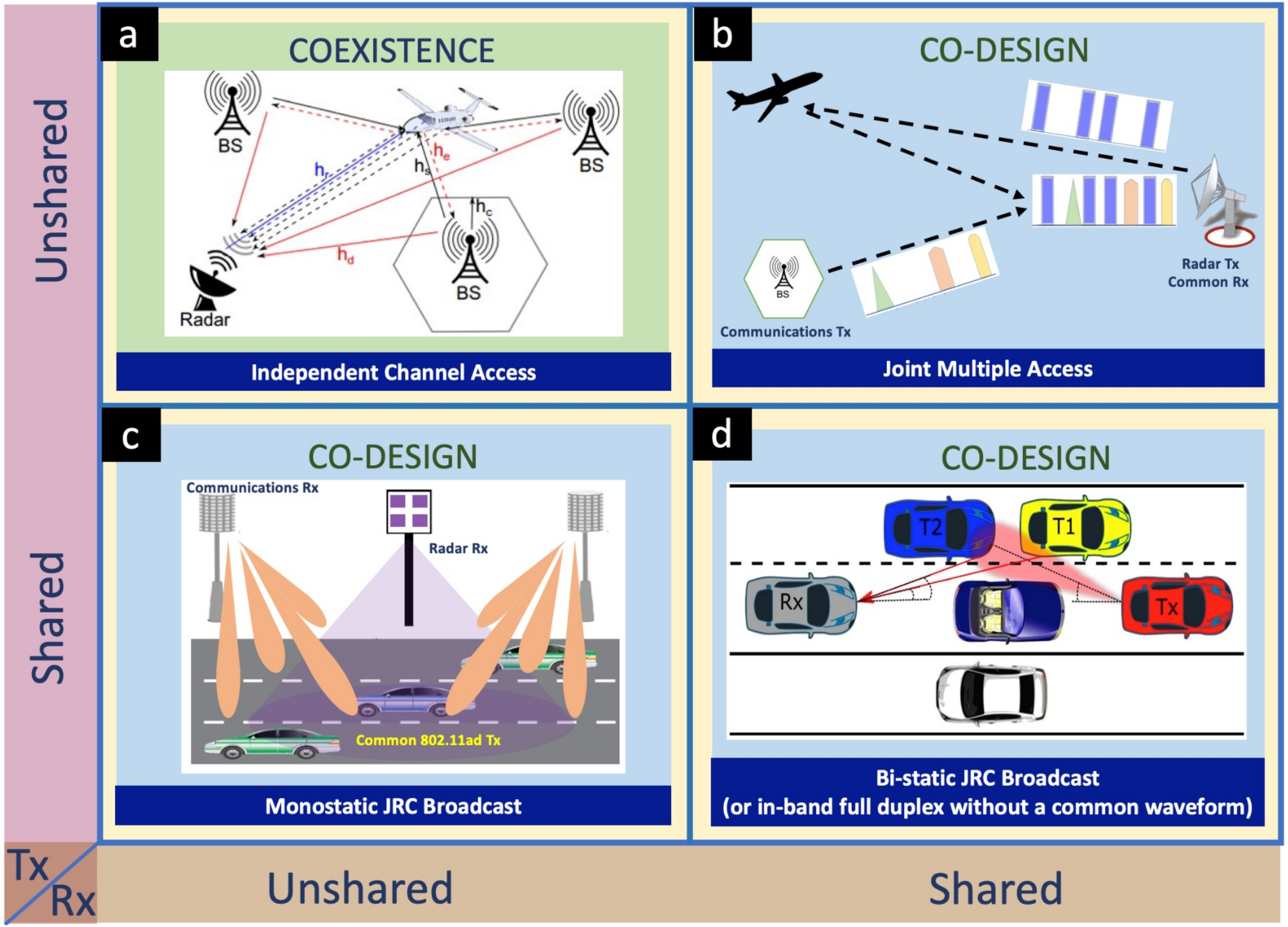
2nd EARS Workshop

Welcome to the 2nd Workshop on ENHANCING ACCESS TO THE RADIO SPECTRUM

OCTOBER 19 - 20, 2015

Sponsored by the National Science Foundation

Integrated Sensing and Communications (ISAC) Topologies



a

COEXISTENCE

Independent Channel Access

b

CO-DESIGN

Joint Multiple Access

c

CO-DESIGN

Monostatic JRC Broadcast

d

CO-DESIGN

Bi-static JRC Broadcast
(or in-band full duplex without a common waveform)

Unshared

Shared

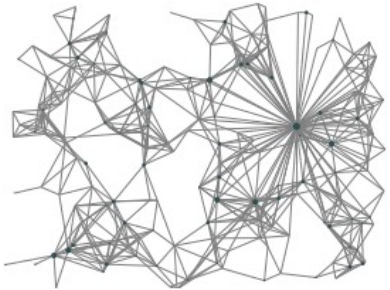
Tx
Rx

Unshared

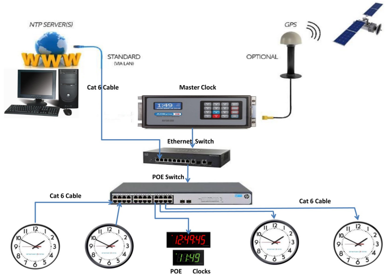
Shared

Distributed ISAC Considerations

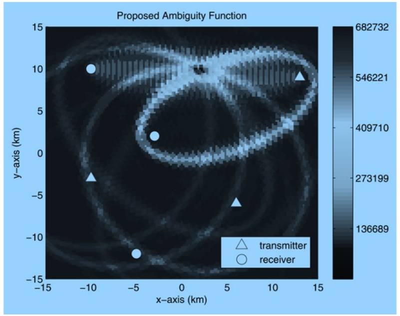
Challenge: Future networks will be more decentralized and edge-focused
Current research devoted to colocated/centralized ISAC



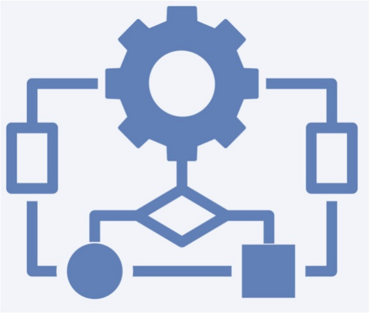
Complexity



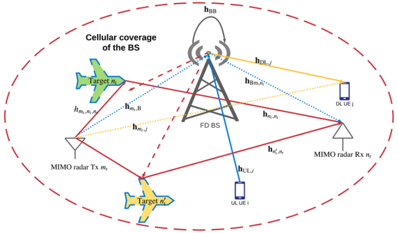
Synchronization



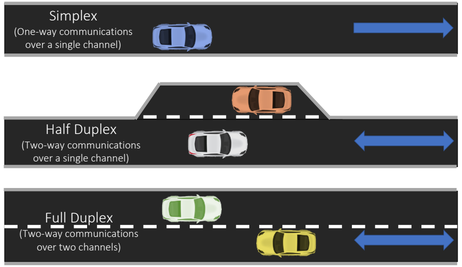
Statistical Design



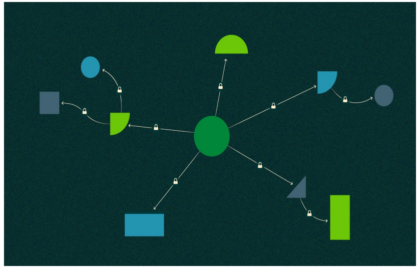
Speed



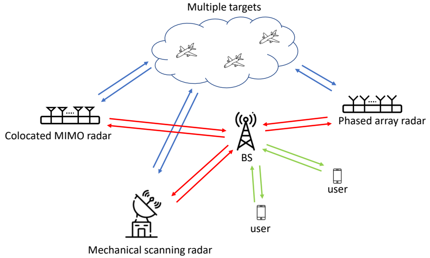
Data Association



Duplexing

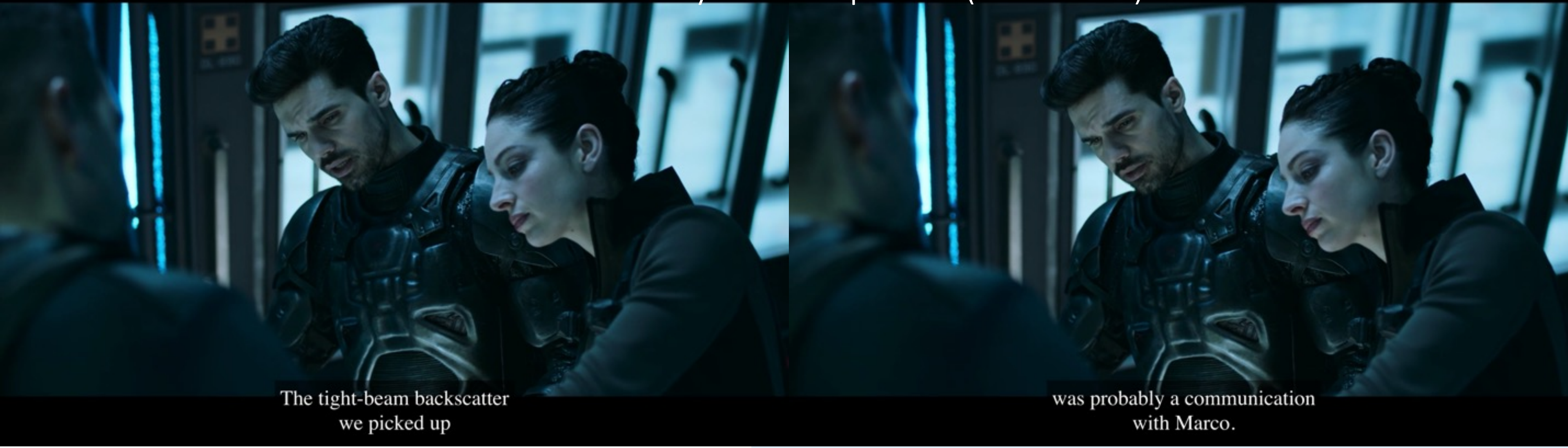


Fusion Center



Architectures

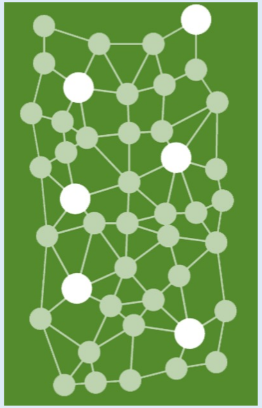
Courtesy: The Expanse (Season 5)



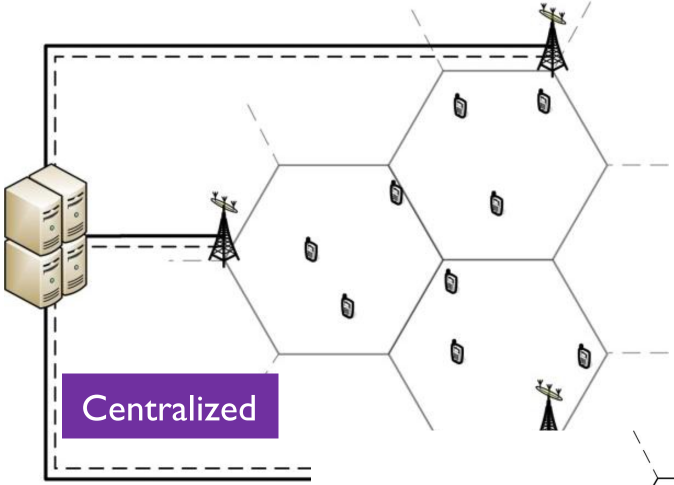
The tight-beam backscatter
we picked up

was probably a communication
with Marco.

Non-Colocated MIMO Communications

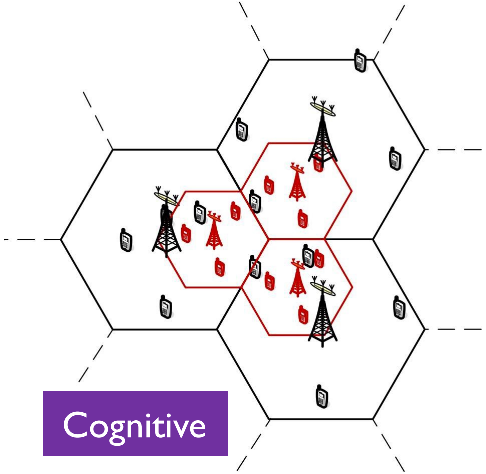


Non-colocated MIMO : Multi-cell, Distributed

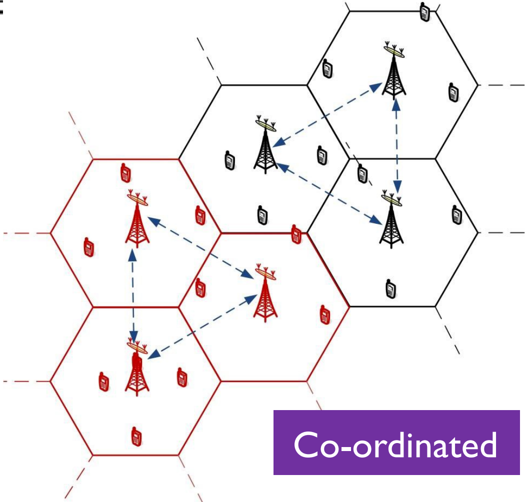


Centralized

© S, Chatzinotas. UL

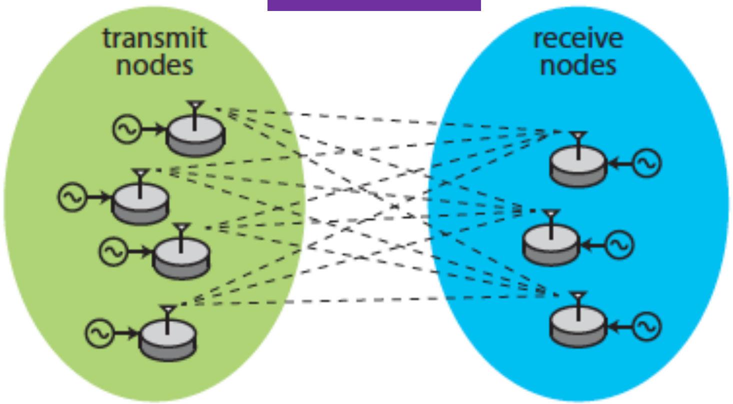


Cognitive



Co-ordinated

Distributed



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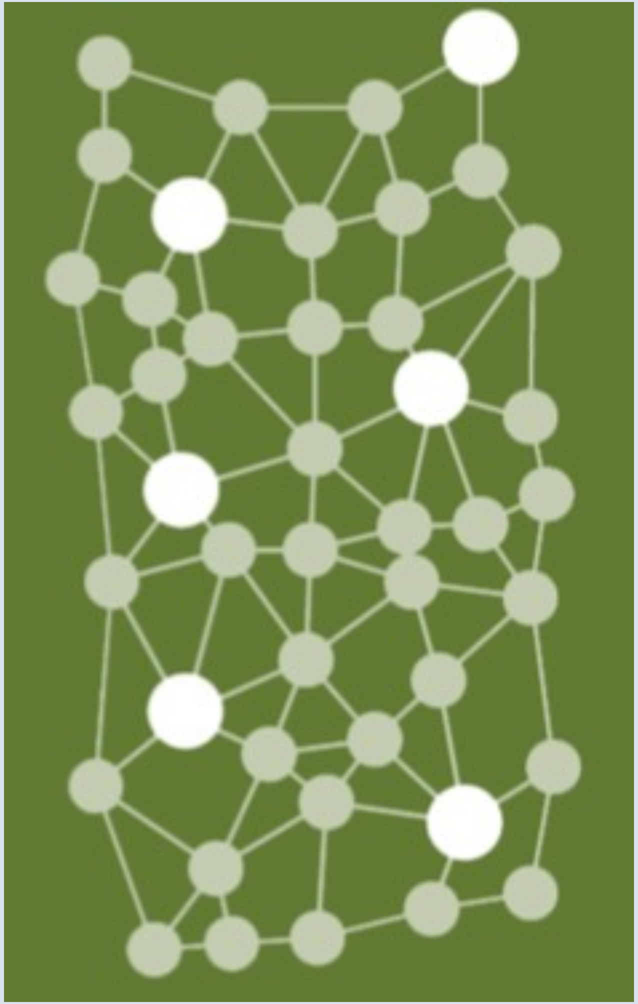
Aim to form large virtual arrays → Massive MIMO

- Synchronization
- Scaling up


Courtesy: Species II

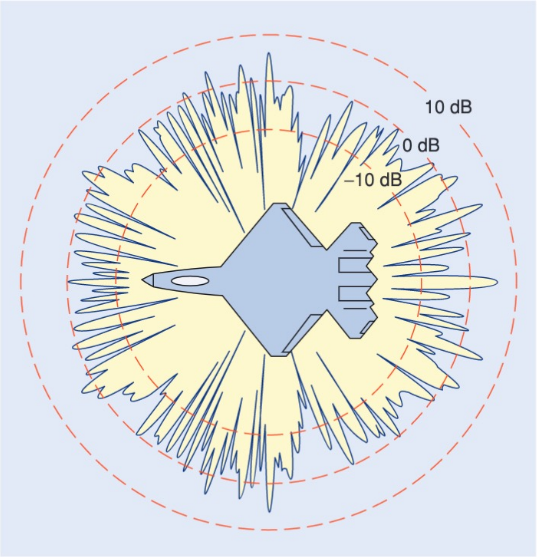
We had a malfunction
in the K.U. band antenna.

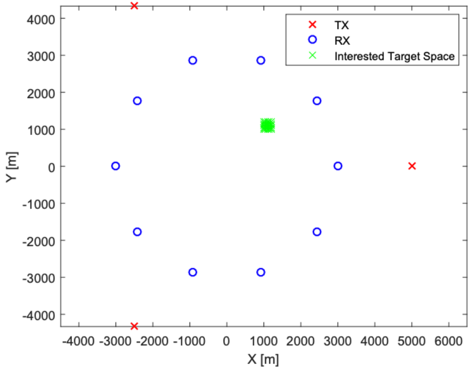
Widely Distributed MIMO Radar



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

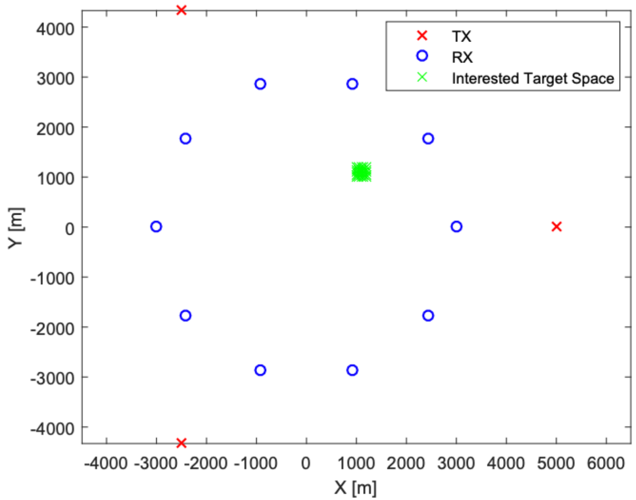




A. M. Haimovich, R. S. Blum and L. J. Cimini, "MIMO Radar with Widely Separated Antennas," in IEEE Signal Processing Magazine, vol. 25, no. 1, pp. 116-129, 2008
S. Sun, K. V. Mishra and A. P. Petropulu, "Target Estimation by Exploiting Low Rank Structure in Widely Separated MIMO Radar," RadarConf 2019.

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 $\mathbf{p}^{(k)}$:



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

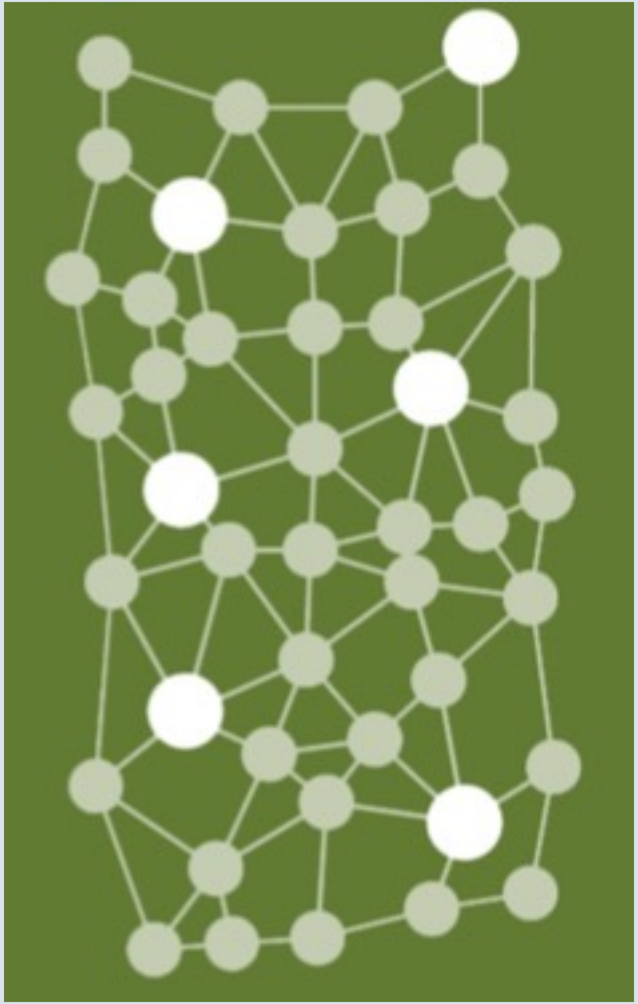
- Doppler frequency $f_{mn}^{(k)}$ is proportional t the target's radial velocity $\mathbf{v}^{(k)}$:

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

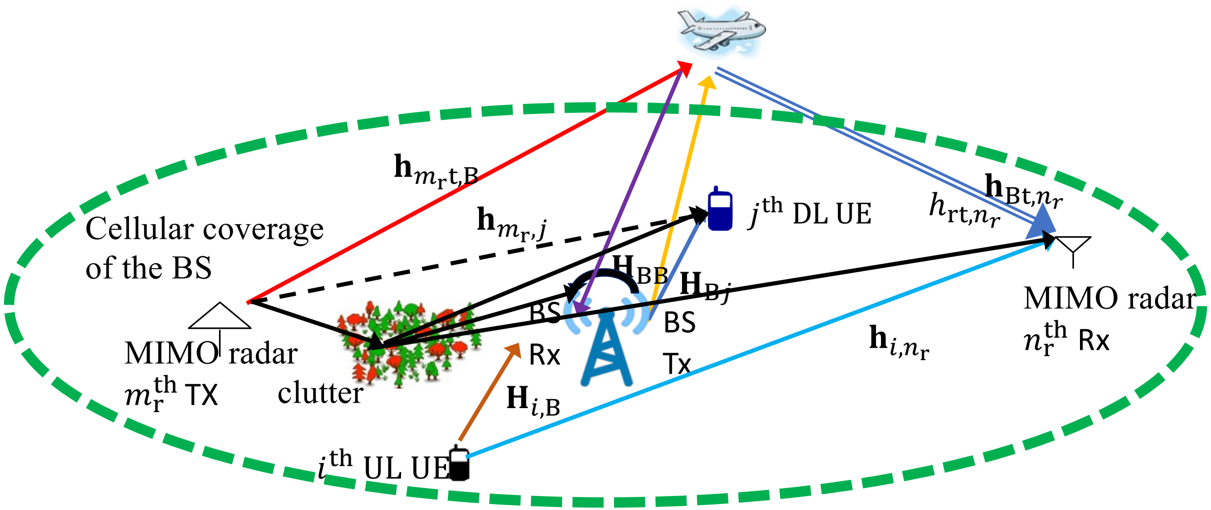
S. Sun, K. V. Mishra and A. P. Petropulu, "Target Estimation by Exploiting Low Rank Structure in Widely Separated MIMO Radar," RadarConf 2019.


Courtesy: The Expanse (S06E05)

Full-Duplex Distributed 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

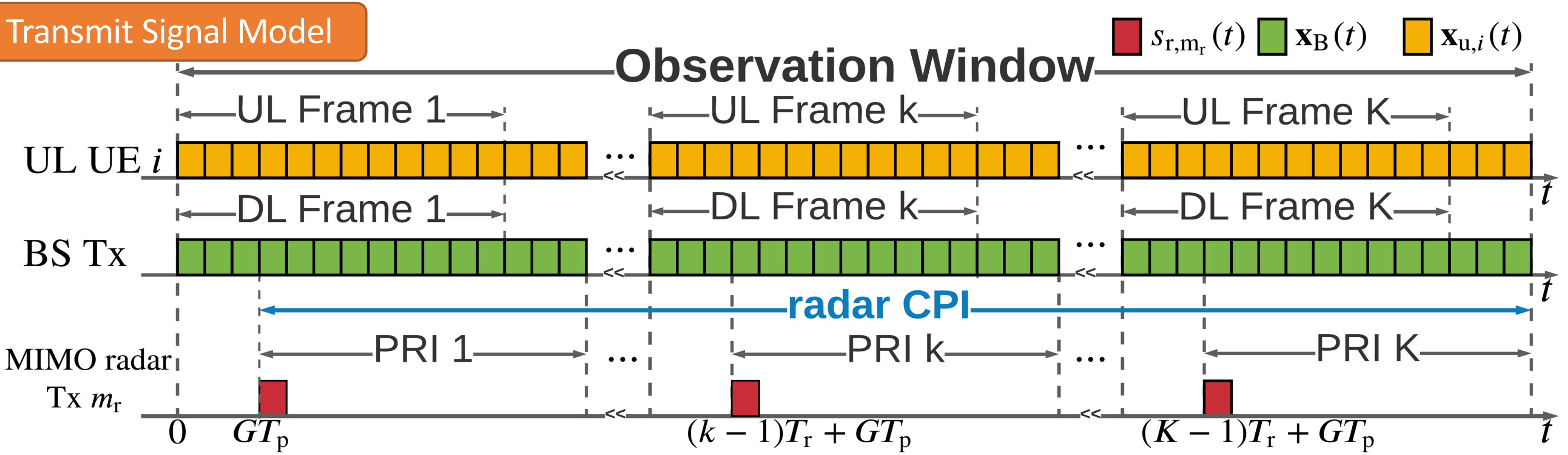
Compounded and weighted sum mutual information as metric

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

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

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}:

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

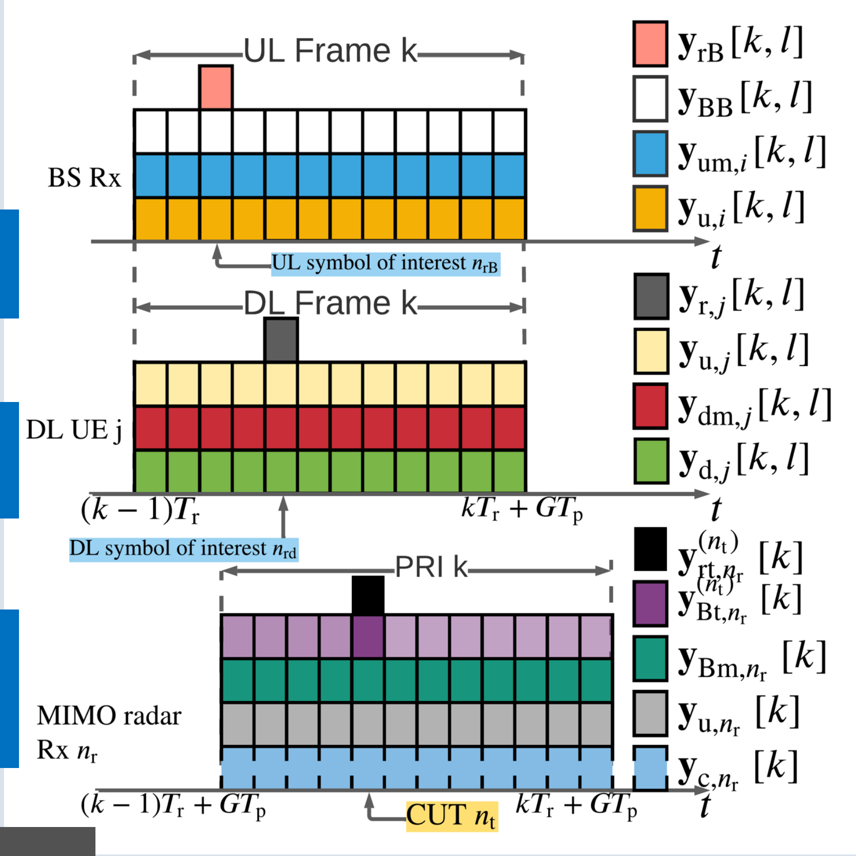
Target reflected DL signal

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

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

subject to

$$\left.\begin{aligned} &\textstyle\sum_{j=1}^{J} \mathrm{tr}\left\{P_{d,j}[k]P_{d,j}^{\dagger}[k]\right\} \leq P_{\mathrm{B}}, \\ &\mathrm{tr}\left\{P_{u,i}[k]P_{u,i}^{\dagger}[k]\right\} \leq P_{\mathrm{u}}, \end{aligned}\right\}$$

DL and UL Power budgets

$$\left.\begin{aligned} &R_j^d[k] \geq R_{\mathrm{DL}}, \\ &R_i^u[k] \geq R_{\mathrm{UL}}, \end{aligned}\right\}$$

QoS constraints

$$\left.\begin{aligned} &\left\|a_{m_r}\right\|^2 = P_{\mathrm{r},m_r}, \\ &\frac{K \max\limits_{k=1,\cdots,K} \left|\boldsymbol{a}_{m_r}[k]\right|^2}{P_{r,m_r}} \leq \gamma_{m_r}, \forall i,j,k,m_r \end{aligned}\right\}$$

PAR for radar codes

Waveform code matrix

$\mathbf{A} = \left[\mathbf{a}^{\intercal}[1],\cdots,\mathbf{a}^{\intercal}[K]\right]$

$= \left[\boldsymbol{a}_1,\cdots,\boldsymbol{a}_{\mathrm{M_r}}\right]$

Non-convex problem solved through BCD algorithm

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

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

Weighted mean square error sum

Weight matrix

Mean square error matrix

Theorem (Liu, Mishra and Saquib, 2020)

Solving the problem

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

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

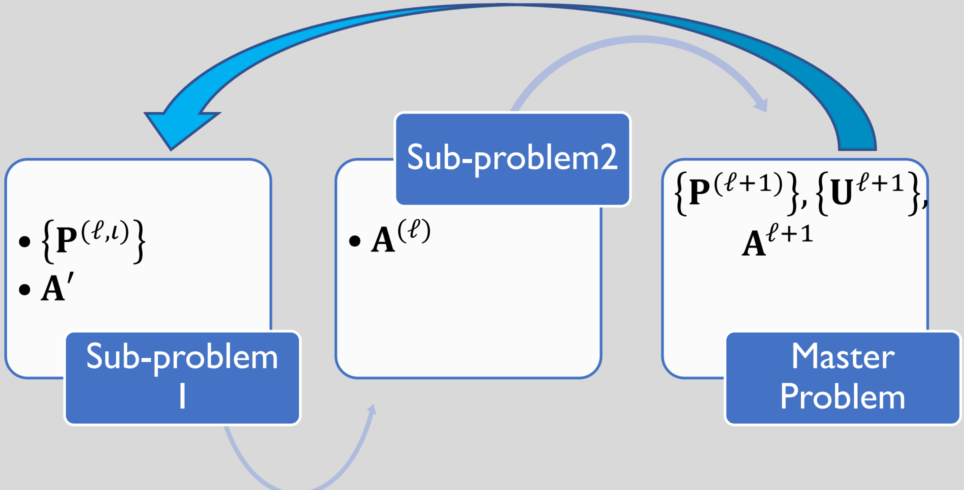
BCD based Iterative Alternating Algorithm

Sub-problem 2: Matrix nearness problem

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

→ a structured tight frame design problem

BCD Iteration Summary



Sub-problem I
- $\{\mathbf{P}^{(\ell,\iota)}\}$
- $\mathbf{A}'$

Sub-problem2
- $\mathbf{A}^{(\ell)}$

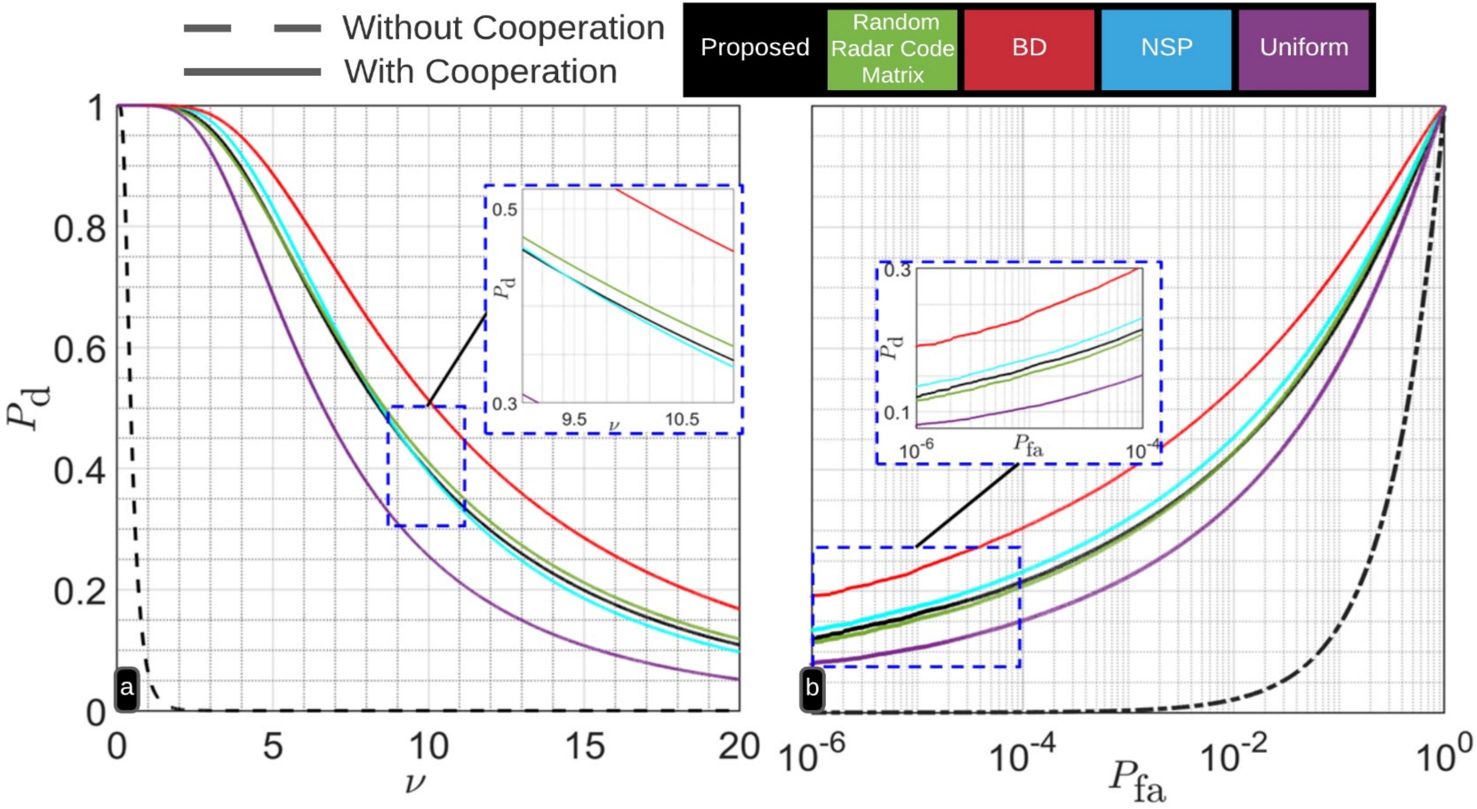
Master Problem

$\{\mathbf{P}^{(\ell+1)}\}, \{\mathbf{U}^{\ell+1}\}, \mathbf{A}^{\ell+1}$

ℓ: iteration index of the master problem

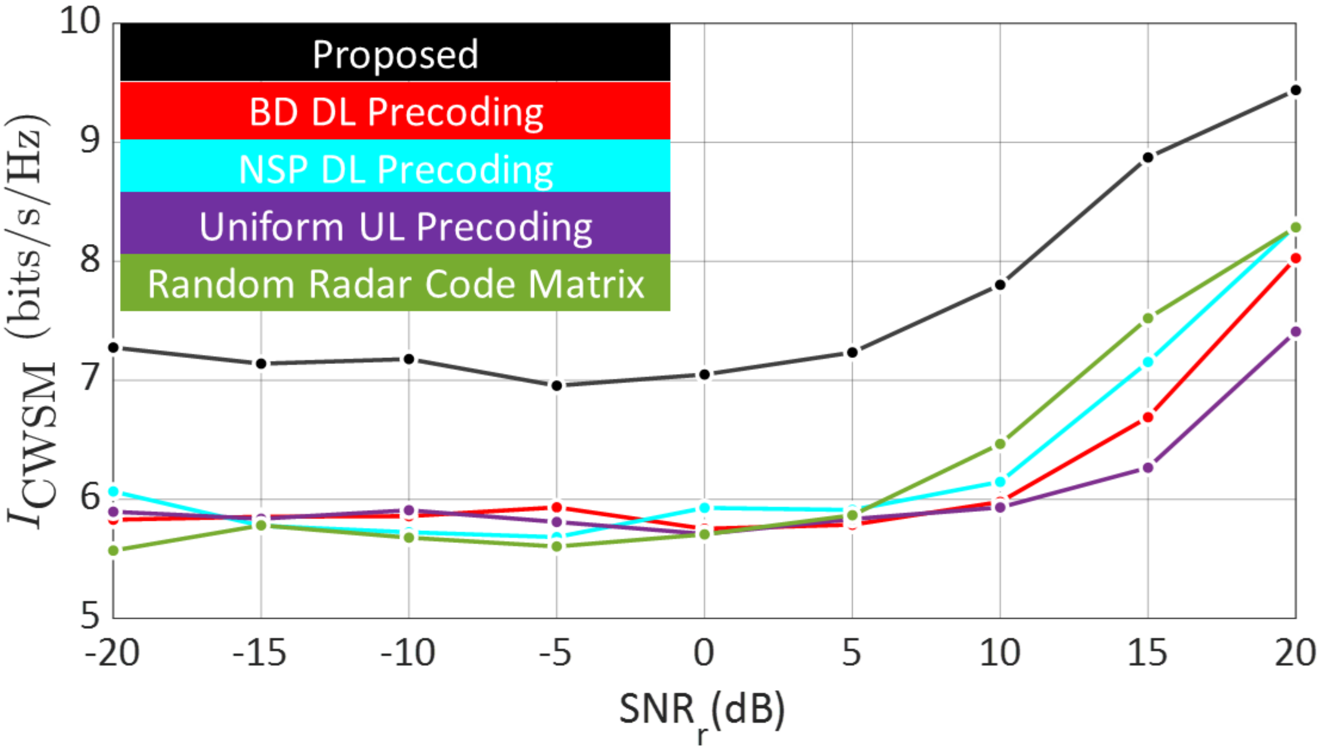
ι: iteration index of the sub-problem 2

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.

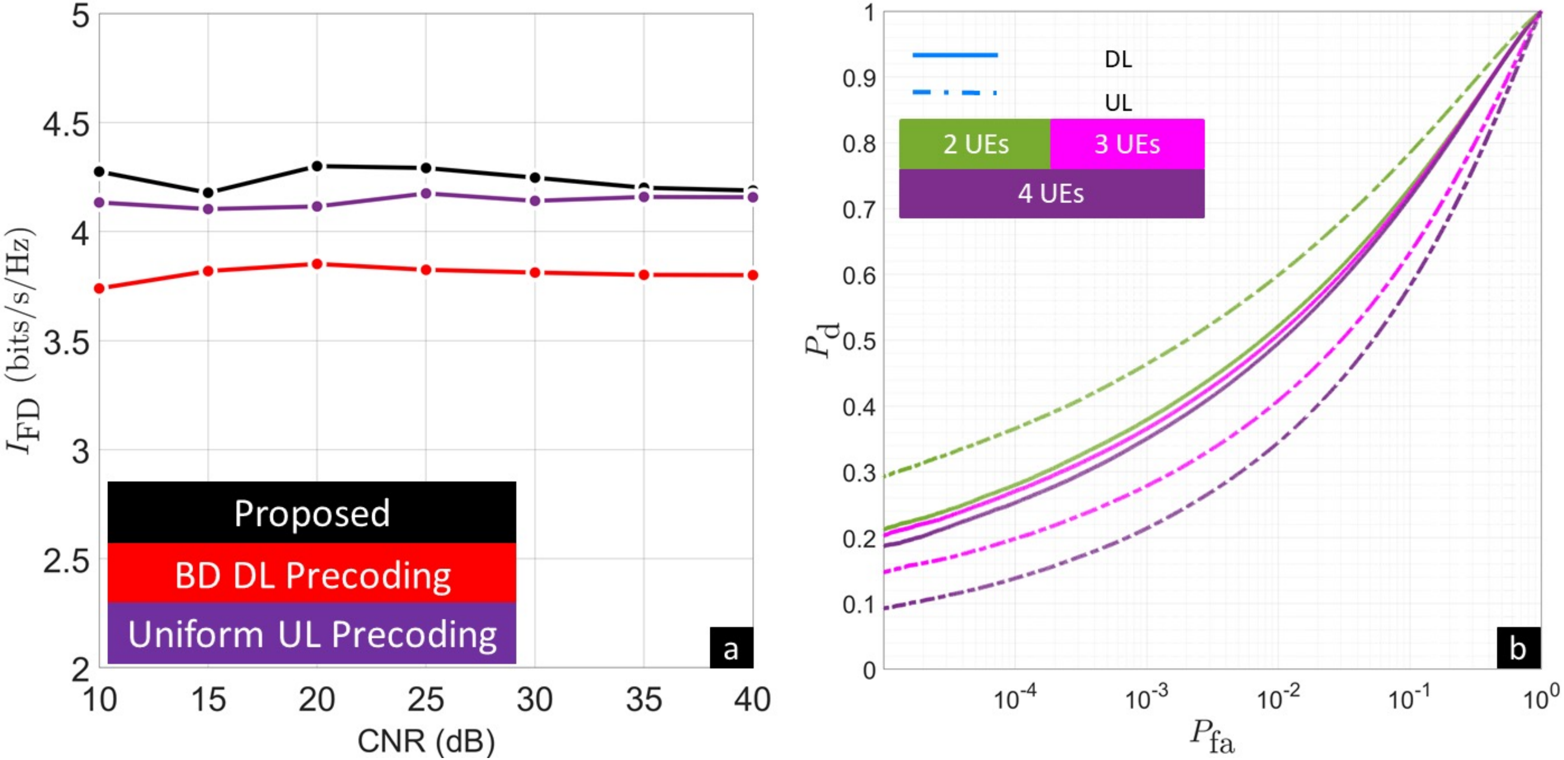
Numerical Experiments



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.

Numerical Experiments



Joint radar and communications analysis: (a) IBFD MU-MIMO performance vs. CNRs (b) ROC curves with varying numbers of UL/DL UEs.

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.

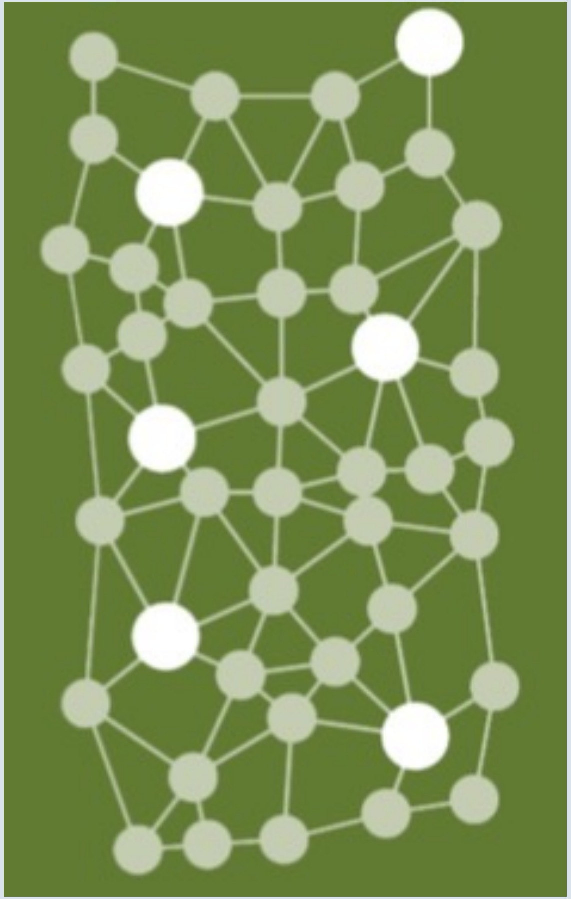
Courtesy:

Battlestar Galactica

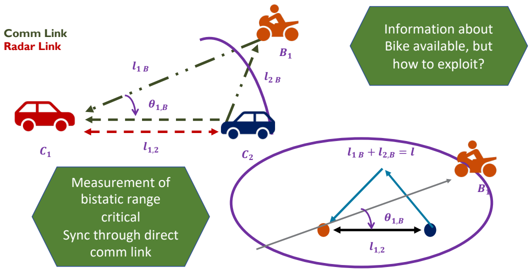
(S01E10)

The decoy ships will jump into the enemy star system at extreme radar range from the Cylon asteroid

Other Distributed ISAC Architectures



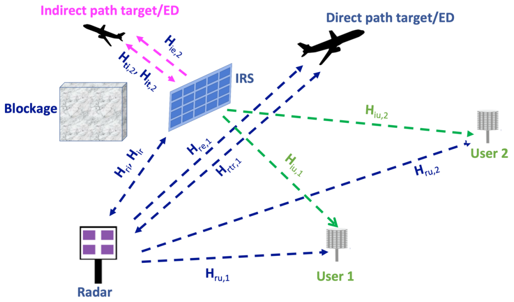
Emerging Distributed JRC/ISAC Trends



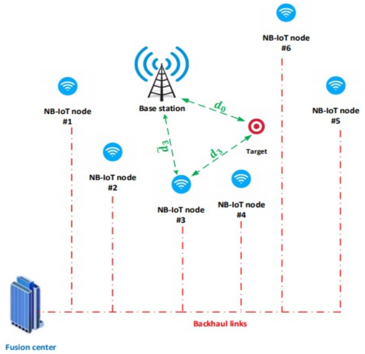
Information about Bike available, but how to exploit?

Measurement of bistatic range critical
Sync through direct comm link

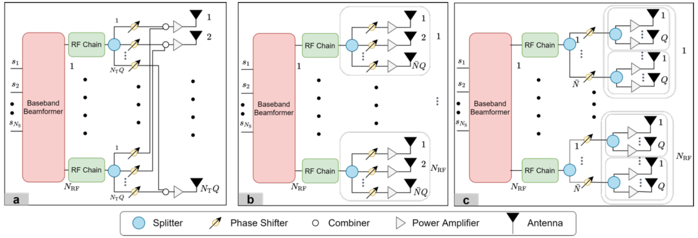
Sensor Fusion



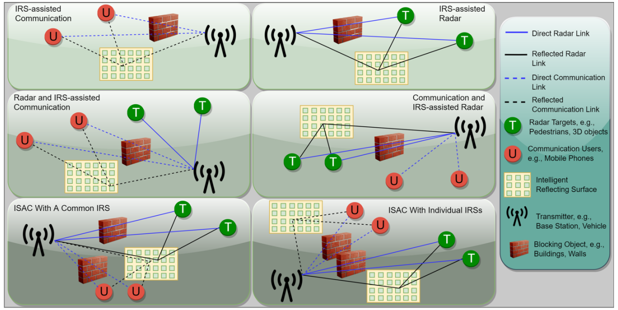
Secure IRS-Aided DFRC



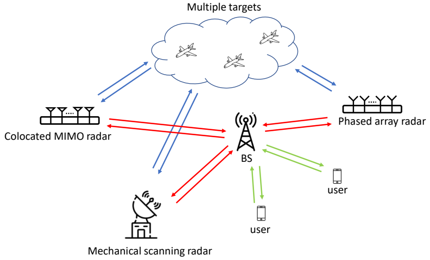
Passive ISAC



THz JRC



IRS-Aided ISAC



Heterogenous ISAC

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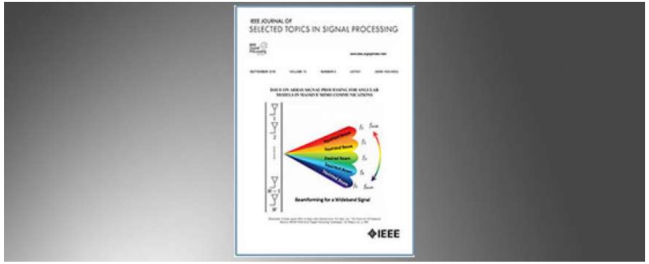

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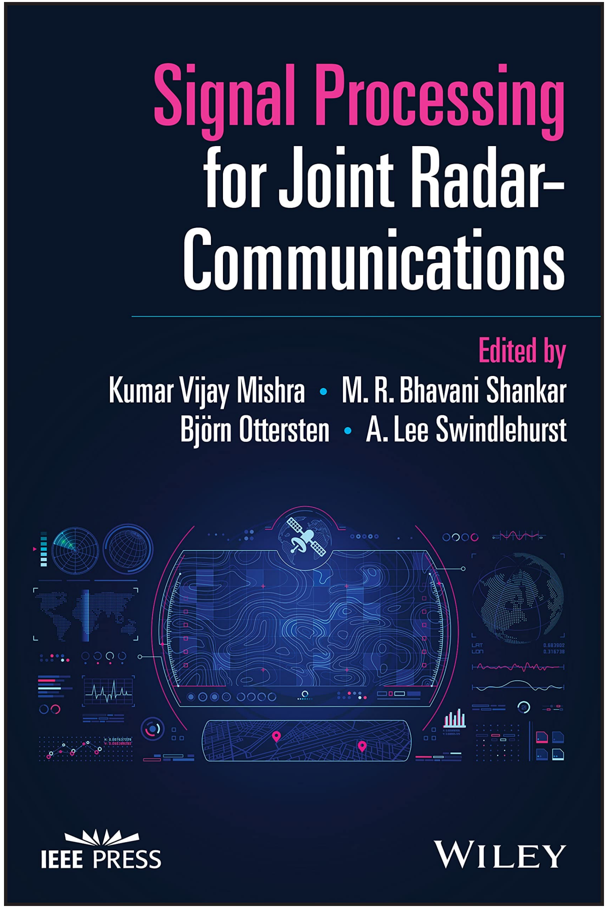
Thank you!



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