WEBINAR SERIES ON ADVANCED MOBILITY
Acknowledgement

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- Editor, IEEE Transactions on Aerospace and Electronic Systems
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- Founding member, IEEE ComSoc ISAC ETI
- Research Interests:
  - Radar
  - Communications
  - Electromagnetics
  - Remote Sensing
  - Signal Processing
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I found my passion in the Army Research Lab.

Motivation
Wireless Communications Trends

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


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

\[ C = n W \log(1 + \text{SINR}) \]

- 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
Sensor-Driven Vehicles

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© 4. Owners, graphic from web
### Automotive Sensors

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

Software-Managed

… and Connected!

Connected Cars Generate Huge Data!

Autonomous Vehicles need high BW

1) To sense accurately
2) To stay connected

Q: Where is the BW?

DSRC

C-V2X

© VW-Software-Anwendungsgebiete. Quelle: VW,
© IEEE, https://spectrum.ieee.org/transportation/advanced-cars/6-key-connectivity-requirements-of-autonomous-driving
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Modern radar/comms operate in an increasingly crowded RF spectrum.

Radar/comms need to use full bandwidth and undertake continuous transmissions.

<table>
<thead>
<tr>
<th>IEEE Radar band</th>
<th>VHF/UHF</th>
<th>L</th>
<th>S</th>
<th>C</th>
<th>X</th>
<th>Ku, K, Ka, V, W</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[30 MHz – 1 GHz]</td>
<td>[1-2 GHz]</td>
<td>[2-4 GHz]</td>
<td>[4-8 GHz]</td>
<td>[8-12 GHz]</td>
<td>[12-300 GHz]</td>
</tr>
</tbody>
</table>

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
Integrated Sensing and Communications (ISAC) Topologies

- **a**. COEXISTENCE
  - Independent Channel Access
  - Joint Multiple Access

- **b**. CO-DESIGN
  - Radar Tx Common Rx

- **c**. CO-DESIGN
  - Monostatic JRC Broadcast

- **d**. CO-DESIGN
  - Bi-static JRC Broadcast (or in-band full duplex without a common waveform)
<table>
<thead>
<tr>
<th>More ISAC Topologies</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Channel Access</strong></td>
</tr>
<tr>
<td>Independent</td>
</tr>
<tr>
<td>Coordinated</td>
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<tr>
<td>Joint</td>
</tr>
<tr>
<td>Shared</td>
</tr>
<tr>
<td><strong>Hardware</strong></td>
</tr>
<tr>
<td>Separate Tx &amp; Rx</td>
</tr>
<tr>
<td>Same Tx, Common Rx</td>
</tr>
<tr>
<td>Common Tx, Same Rx</td>
</tr>
<tr>
<td>Common Tx &amp; Rx</td>
</tr>
<tr>
<td><strong>Waveform</strong></td>
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<tr>
<td>Separate</td>
</tr>
<tr>
<td>Common</td>
</tr>
<tr>
<td>Resource-shared</td>
</tr>
<tr>
<td><strong>Location</strong></td>
</tr>
<tr>
<td>Colocated</td>
</tr>
<tr>
<td>Bi-static</td>
</tr>
<tr>
<td>Distributed</td>
</tr>
<tr>
<td>Networked</td>
</tr>
<tr>
<td>Heterogeneous</td>
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<tr>
<td><strong>Performance/Functionality</strong></td>
</tr>
<tr>
<td>Radar-centric</td>
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<tr>
<td>Comms-centric</td>
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<tr>
<td>Joint radar-comms</td>
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<tr>
<td>Dual-Function Radar-Comms</td>
</tr>
<tr>
<td><strong>Specialized</strong></td>
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<tr>
<td>MRMC</td>
</tr>
<tr>
<td>IBFD ISAC</td>
</tr>
<tr>
<td>IRS-Aided ISAC</td>
</tr>
<tr>
<td>mmWave, THz, VLC, quantum</td>
</tr>
</tbody>
</table>
Outline

Spectral Co-Design
- Motivation & Challenges
- Automotive JRC, Full-Duplex ISAC, Learning

Opportunistic ISAC
- Wi-Fi Protocol for Radar, Weather Sensing

Spectral Co-Existence
- Dual-Blind Deconvolution
It'll be on the sail by the antenna array.

Spectral Co-Design
Automotive JRC

Courtesy: Citadel (S01E06)
Monostatic and Bi-Static Systems

- 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:** How do these properties compare in JRC mode?
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
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

Duke will maintain altitude at 5,000 feet to avoid radar.

Courtesy: Citadel (S01E06)
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**

- Half Duplex (Two-way communications over a single channel)
- Full Duplex (Two-way communications over two channels)
**Target RCS is not identical for all Tx-Rx pairs; modeled statistically**

**Radar 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**

---

Spectral Codesign System model

Transmit Signal Model

**Observation Window**

UL UE $i$: $x_{u,i}(t) = \sum_{j=1}^{J} \sum_{k=0}^{K-1} \sum_{l=0}^{N-1} p_{d,j}[k] d_{d,j}[k, l] p_T(t - (kN + l)T_p)$

BS Tx: $x_B(t) = \sum_{j=1}^{J} \sum_{k=0}^{K-1} \sum_{l=0}^{N-1} p_{d,j}[k] d_{d,j}[k, l] p_T(t - (kN + l)T_p)$

Spectral Codesign System model

Composite Receive Signal Model

Receive Signal at BS Rx to decode UL UE $i$:
$$y_{i}^{u}[k, l] = y_{u,i}[k, l] + y_{um,i}[k, l] + y_{rB}[k, l] + y_{BB}[k, l] + z_{B}[k, l]$$

- Multiuser-interference
- FD Self-interference

Receive Signal at DL UE $j$:
$$y_{j}^{d}[k, l] = y_{d,j}[k, l] + y_{dm,j}[k, l] + y_{u,j}[k, l] + y_{r,j}[k, l] + z_{d,j}[k, l]$$

- UL interfering signal

Receive Signal at radar Rx $n_r$:
$$y_{n_r}^{r}[k] = y_{rt,n_r}[k] + y_{Bt,n_r}[k] + y_{Bm,n_r}[k] + y_{u,n_r}[k] + y_{c,n_r}[k] + z_{r,n_r}[k]$$

- Target reflected DL signal
- Multi-path propagated DL signal
- UL signal
- Clutter signal

Complex Gaussian Noise vectors
Numerical Experiments

The tight-beam backscatter we picked up was probably a communication with Marco.

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.

THz ISAC Hybrid Beamforming via Deep Learning

Major Challenges 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

THz ISAC Hybrid Beamforming via Deep Learning

Major Challenges 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

Communications

\[
\begin{align*}
\text{min}_{\mathbf{F}_{RF}, \{\mathbf{F}_{BB}[m]\}_{m \in \mathcal{M}}} & \quad \frac{1}{M} \sum_{m \in \mathcal{M}} \| \mathbf{F}_{RF} \mathbf{F}_{BB}[m] - \mathbf{F}_{C}[m] \|_\mathcal{F} \\
\text{s.t.} & \quad \sum_{m \in \mathcal{M}} \| \mathbf{F}_{RF} \mathbf{F}_{BB}[m] \|_\mathcal{F} = MN_S, \\
& \quad |[\mathbf{F}_{RF}]_{i,j}| = \frac{1}{\sqrt{N_T}}, \quad \forall i, j.
\end{align*}
\]

Radar

\[
\begin{align*}
\text{min}_{\mathbf{F}_{RF}, \{\mathbf{F}_{BB}[m]\}_{m \in \mathcal{M}}, \{\mathbf{P}[m]\}_{m \in \mathcal{M}}} & \quad \frac{1}{M} \sum_{m \in \mathcal{M}} \| \mathbf{F}_{RF} \mathbf{F}_{BB}[m] - \mathbf{F}_R \mathbf{P}[m] \|_\mathcal{F} \\
\text{s.t.} & \quad \sum_{m \in \mathcal{M}} \| \mathbf{F}_{RF} \mathbf{F}_{BB}[m] \|_\mathcal{F} = MN_S, \\
& \quad |[\mathbf{F}_{RF}]_{i,j}| = \frac{1}{\sqrt{N_T}}, \quad \forall i, j, \\
& \quad \mathbf{P}[m] \mathbf{P}^H[m] = \mathbf{I}_{N_S}
\end{align*}
\]

JRC Hybrid Beamforming Design

\[
\begin{align*}
\text{min}_{\mathbf{F}_{RF}, \{\mathbf{F}_{BB}[m]\}_{m \in \mathcal{M}}, \{\mathbf{P}[m]\}_{m \in \mathcal{M}}} & \quad \frac{1}{M} \sum_{m \in \mathcal{M}} \left( \eta \| \mathbf{F}_{RF} \mathbf{F}_{BB}[m] - \mathbf{F}_{C}[m] \|_\mathcal{F} + \bar{\eta} \| \mathbf{F}_{RF} \mathbf{F}_{BB}[m] - \mathbf{F}_R \mathbf{P}[m] \|_\mathcal{F} \right) \\
\text{s.t.} & \quad \sum_{m \in \mathcal{M}} \| \mathbf{F}_{RF} \mathbf{F}_{BB}[m] \|_\mathcal{F} = MN_S, \\
& \quad |[\mathbf{F}_{RF}]_{i,j}| = \frac{1}{\sqrt{N_T}}, \quad \forall i, j \in \mathcal{S}, |[\mathbf{F}_{RF}]_{i,j}| = 0, \quad \forall i, j \in \bar{\mathcal{S}}, \\
& \quad \mathbf{P}[m] \mathbf{P}^H[m] = \mathbf{I}_{N_S}
\end{align*}
\]
THz ISAC Hybrid Beamforming via Deep Learning

THz ISAC Hybrid Beamforming via Deep Learning

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

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

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Current literature</th>
<th>Proposed radar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range</td>
<td>Long range (200m)</td>
<td>Short range (40m)</td>
</tr>
<tr>
<td>Target model</td>
<td>Simple point targets</td>
<td>Extended targets</td>
</tr>
<tr>
<td>Type of target</td>
<td>Static targets</td>
<td>Dynamic targets</td>
</tr>
<tr>
<td>Golay sequence</td>
<td>Standard</td>
<td>Modified / Doppler resilient</td>
</tr>
</tbody>
</table>
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**

  \[ G_{aN}[n] * G_{aN}[-n] + \]

- **Frequency-domain Property: Constant spectrum**

  \[ |F_{aN}[k]|^2 + |F_{bN}[k]|^2 = 2N \]
Good Autocorrelation, but Doppler Resilience?

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

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

RQ1
Doppler Resilient Preamble

RQ2
Identical field width

RQ3
Receiver operation unchanged

Extended Target Modeling (via PyBullet)

Extended Target Modeling Results – Multiple Targets
802.11ad-Based UAV-Borne Radar

Surface clutter models and PyBullet modeling used to obtain the signatures

Spectral Co-Existence
Dual-Blind Deconvolution

We had a malfunction in the K.U. band antenna.
Problem: Neither the transmitted signals nor the channels are known

**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:
\[ \sum_{\ell=0}^{L-1} \left[ \alpha_r \right]_{\ell} \delta(t - \left[ \bar{\tau}_r \right]_{\ell}) e^{-j2\pi[\bar{\nu}_r]_{\ell}t} \]

Transmitted communications signal:
\[ \sum_{p=0}^{P-1} \sum_{k=0}^{K-1} \left[ g_p \right]_k e^{-j2\pi k\Delta f(t-pT)} \]

Communications channels:
\[ \sum_{q=0}^{Q-1} \left[ \alpha_c \right]_q \delta(t - \left[ \bar{\tau}_c \right]_q) e^{-j2\pi[\bar{\nu}_c]q[t} \]

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

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

**PRI** \( T \)  
Radar waveform \( s \)

Propagation paths \( Q \)  
Symbols \( g \)

Radar targets \( L \)  
Time delay \( \tau \)

Subcarriers \( K \)  
Attenuation \( \alpha \)

Transmitted pulses \( P \)  
Doppler \( \nu \)
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

\[\mathcal{A}_r = \left\{ u\alpha(r)^H : r \in [0,1]^2, \|u\|_2 = 1 \right\}\]

\[\mathcal{A}_c = \left\{ v\alpha(c)^H : c \in [0,1]^2, \|v\|_2 = 1 \right\}\]

The corresponding atomic norm are given by

\[||Z_r||_{\mathcal{A}_r} = \inf_{[\alpha_r]_\ell, r_\ell \in [0,1]^2, \|u\|_2 = 1} \{\sum_\ell |[\alpha_r]_\ell| |Z_r = \sum_\ell [\alpha_r]_\ell a(r_\ell) u^H\}\]

\[||Z_c||_{\mathcal{A}_c} = \inf_{[\alpha_c]_q, c_\ell \in [0,1]^2, \|v\|_2 = 1} \{\sum_q |[\alpha_c]_q| |Z_c = \sum_q [\alpha_c]_q a(c_\ell) v^H\}\]

The primal optimization problem is given by

\[
\begin{align*}
\text{minimize} & \quad ||Z_r||_{\mathcal{A}_r} + ||Z_c||_{\mathcal{A}_c} \\
\text{subject to} & \quad y = \kappa_r(Z_r) + \kappa_c(Z_c)
\end{align*}
\]
Localization for single Rx


Other Distributed ISAC Architectures

Well, except for the com static, I'm piping out on all frequencies. We'll show up on their screen as a radar glitch if they aren't looking close.
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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