Integration Sensing and Communication for 6G:
Waveform Design, Resource Allocation, Application and Prototype Demo

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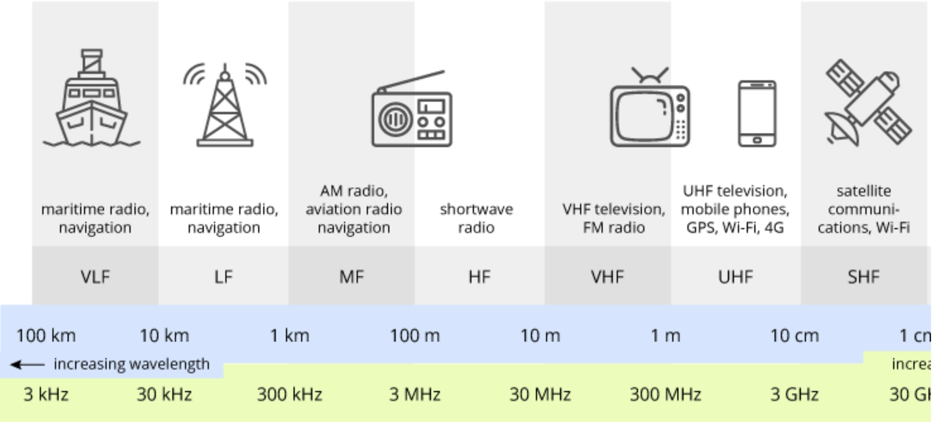
Outline

- **Motivation for ISAC**
  - Fundamental
  - OFDM/OTFS/ODDM
  - Performance Tradeoff
- **Applications**
  - Cross-domain Waveform Design
  - Multiuser Resource Allocation
  - RIS-ISAC: DISCO PLS Attack
  - High Speed Train
  - Optical ISAC
- **Prototype Demos and Standardization**
- **Conclusion and Future Works**

Integrated Sensing and Communications

- Communications and radar are major consumers of wireless spectrum that is facing resource shortage. It improves the efficiency to share the spectrum between communications and radar.

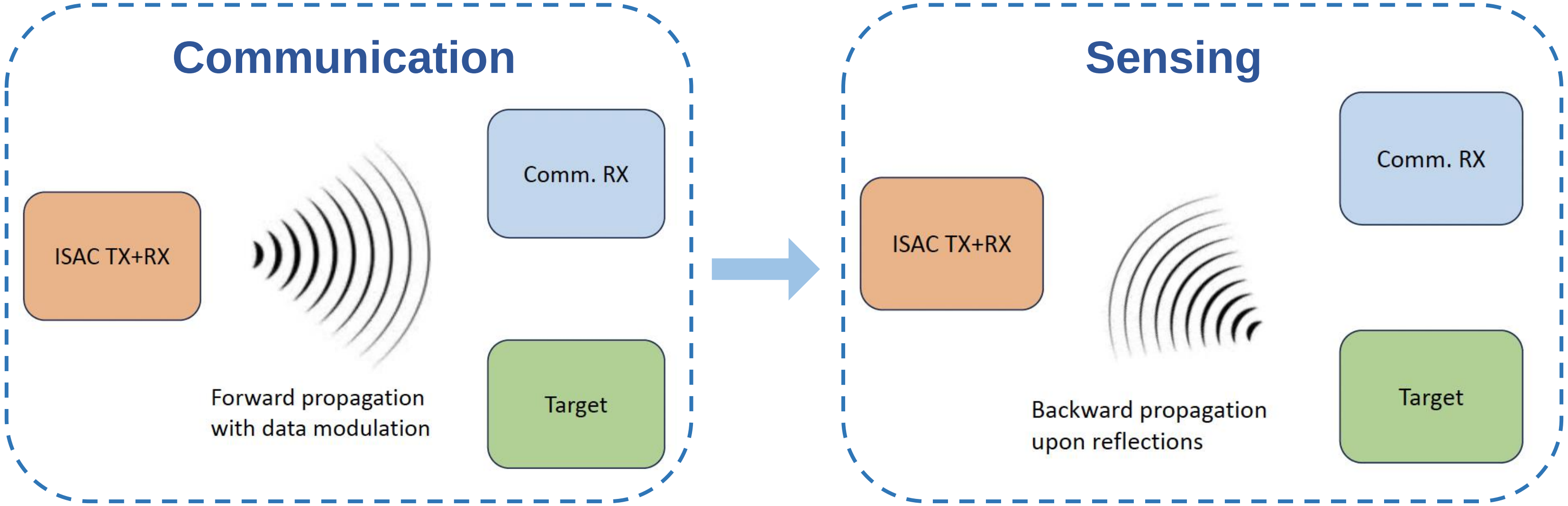


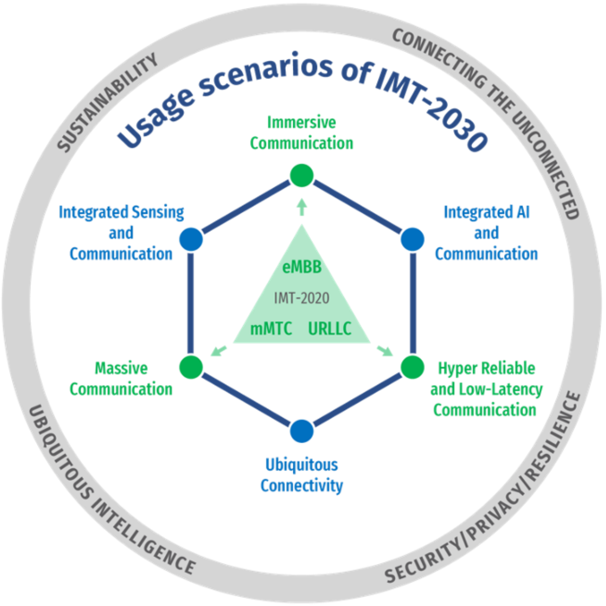
Massive communication and sensing demands

Limited spectrum resources

Integrated Sensing and Communications

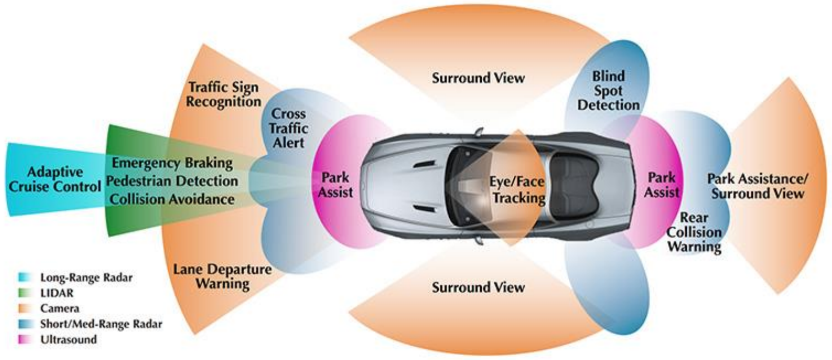
- In ISAC, the waveform completes communications in the forward propagation, and then sensing in the backward propagation.
- ISAC is one of ITU usage scenarios of future 6G systems



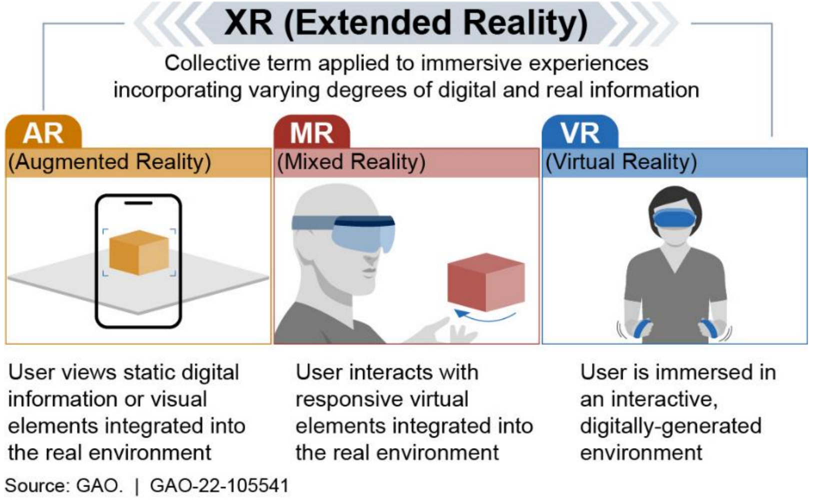


ISAC Use Cases

Autonomous Vehicles

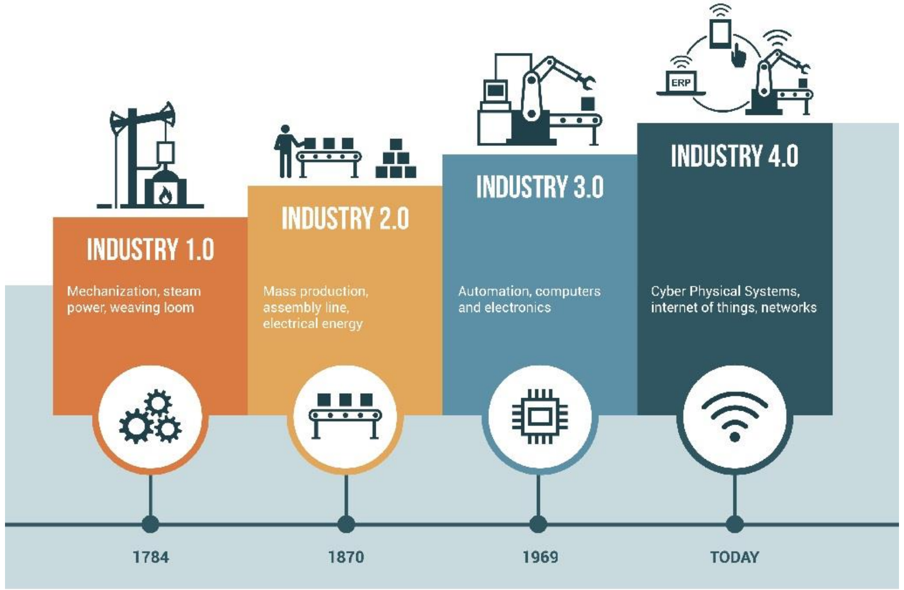


Extended Reality (XR)



Security and Surveillance

Internet of Things



Space Communications

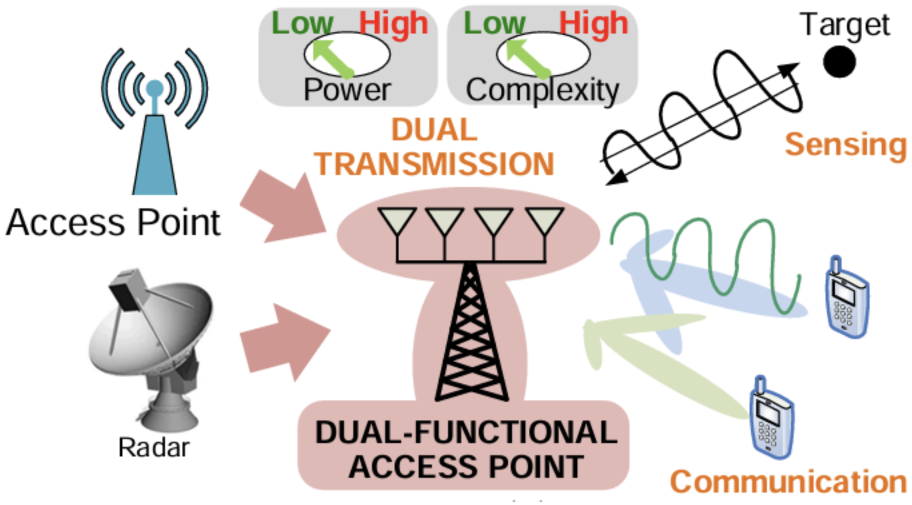
Other Applications

- Entertainments
- Maritime
- Public Safety
- Disaster management
- Agriculture
- Smart Home/City
- Healthcare
- …

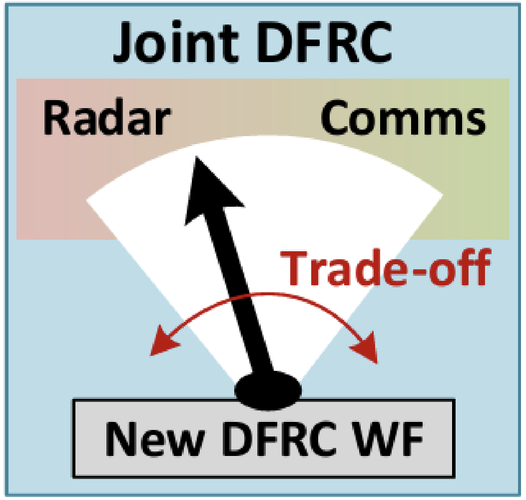
Dual-Function Radar Communication (DFRC)

- By designing signals and systems capable of fulfilling both radar and communication simultaneously, DFRC achieves significant resource efficiency.
- DFRC Techniques: Waveform Design, MIMO, Signal Processing, Hardware Sharing, Coding/Modulation, and Resource Allocation
- Key Challenges: Trade-Off, Interference, Complexity and Regulation

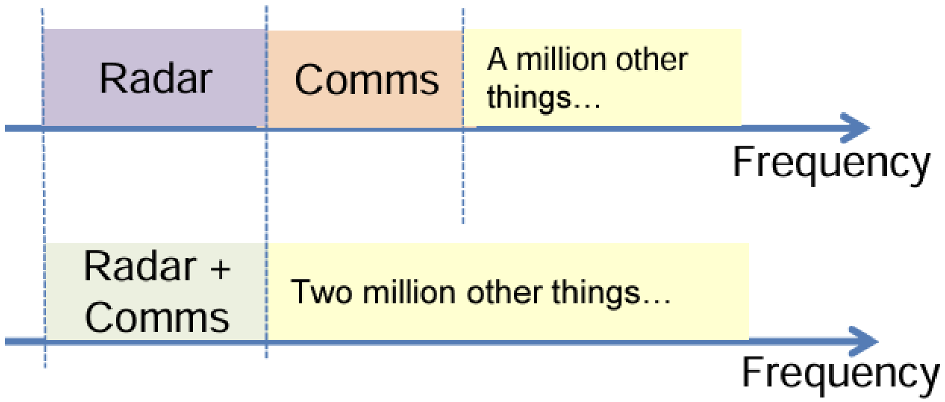
Hardware Gain



Scalable Trade-offs



Spectrum Gain



From DFRC to ISAC

- DFRC is a subset of ISAC, focusing share waveforms, antennas, and processing chains for radar and communication in a shared hardware.
- ISAC can use other devices' separate hardware for broader applications.

Aspect	DFRC	ISAC
Waveform Design	Focuses on **dual-function** waveforms that serve both radar and communication.	Includes **dual-function** waveforms but also explores resource allocation and coordination across systems.
Hardware	Requires **shared hardware** (antennas, transceivers, etc.).	May use **separate hardware** but coordinated operation.
Sensing Capability	Emphasizes radar-based sensing (e.g., object detection, velocity estimation).	Broader sensing, including RF sensing, environmental mapping, and localization.
Application	Radar-centric systems with communication support.	General systems where sensing and communication are equally important.

Waveform Comparison: OFDM/OTFS/ODDM

- **OFDM** is mature technology used in WiFi, 4G/5G/6G. Subcarriers can be used for radar sensing and communication simultaneously.
- **OTFS** modulate data in the delay-Doppler domain, using 2D inverse symplectic Fourier transform (ISFFT)
- **ODDM** directly uses orthogonal basis functions specifically designed to maintain orthogonality in the delay- Doppler domain.

Aspect	OFDM	OTFS	ODDM
Domain	Time-Frequency	Delay-Doppler	Delay-Doppler
Sensing Resolution	Low	High	Very High
Doppler Robustness	Low	High	High
Complexity	Low	Moderate	High
Maturity	High	Moderate	Low
Applications	Static or low-mobility	High-mobility environments	Emerging ISAC applications

Waveform Comparison: OTFS/ODDM

- **OTFS** can introduce leakage effects, PAPR, simple implementation
- **ODDM** is based on orthogonal pulses specific for ISAC in Delay-Doppler domain, multiuser case, but still early research phase.

Aspect	OTFS	ODDM
Modulation Domain	Delay-Doppler (mapped to Time-Frequency)	Pure Delay-Doppler
Orthogonality	Indirect via ISFFT (time-frequency)	Direct in Delay-Doppler domain
Implementation Complexity	Higher (requires ISFFT and IFFT)	Lower (direct modulation in Delay-Doppler)
Waveform Design	OFDM-like	Delay-Doppler pulses
Focus	Communication-centric with sensing support	Joint sensing and communication
Maturity	More mature	Emerging

Fundamental Tradeoff

Fundamental tradeoff between sensing and communication arises from the dual use of shared resources (e.g., spectrum, power, hardware) for two distinct purposes, each with different and often conflicting requirements.

Aspect	Sensing Requirement	Communication Requirement	Resulting Tradeoff
Spectrum	Wide bandwidth for high resolution	Efficient bandwidth for high data rates	Pareto Optimality
Signal Design	Deterministic waveforms	Random-modulated signals	Challenging joint signal optimization
Power	High transmit power	Power-efficient communication	Power sharing impacts one function
Time Resource	Continuous operation	Low-latency data transmission	Time-division sharing reduces capacity
Spatial Resource	Wide/directional beams	Narrow beams for multi-user access	Beam pattern must balance both needs
Interference	Tolerates minimal noise	Tolerates minimal radar clutter	Complex interference mitigation required
DD and TF Resolution	delay-Doppler domain	time-frequency efficiency for multiplexing	Signal optimized for one domain may sacrifice performance in the other domain
Hardware	high-performance antennas, high-power amplifiers, and precise timing for sensing	spectral efficiency and multi-user connectivity	lead to suboptimal performance
Latency	low-latency feedback for real-time tracking	tolerate slightly higher latency for non-real-time data.	Prioritizing one function's latency requirements may impact the other
Standardization	Frequency allocation regulations	spectral efficiency and emission standards	Compromises in signal design and resource allocation.

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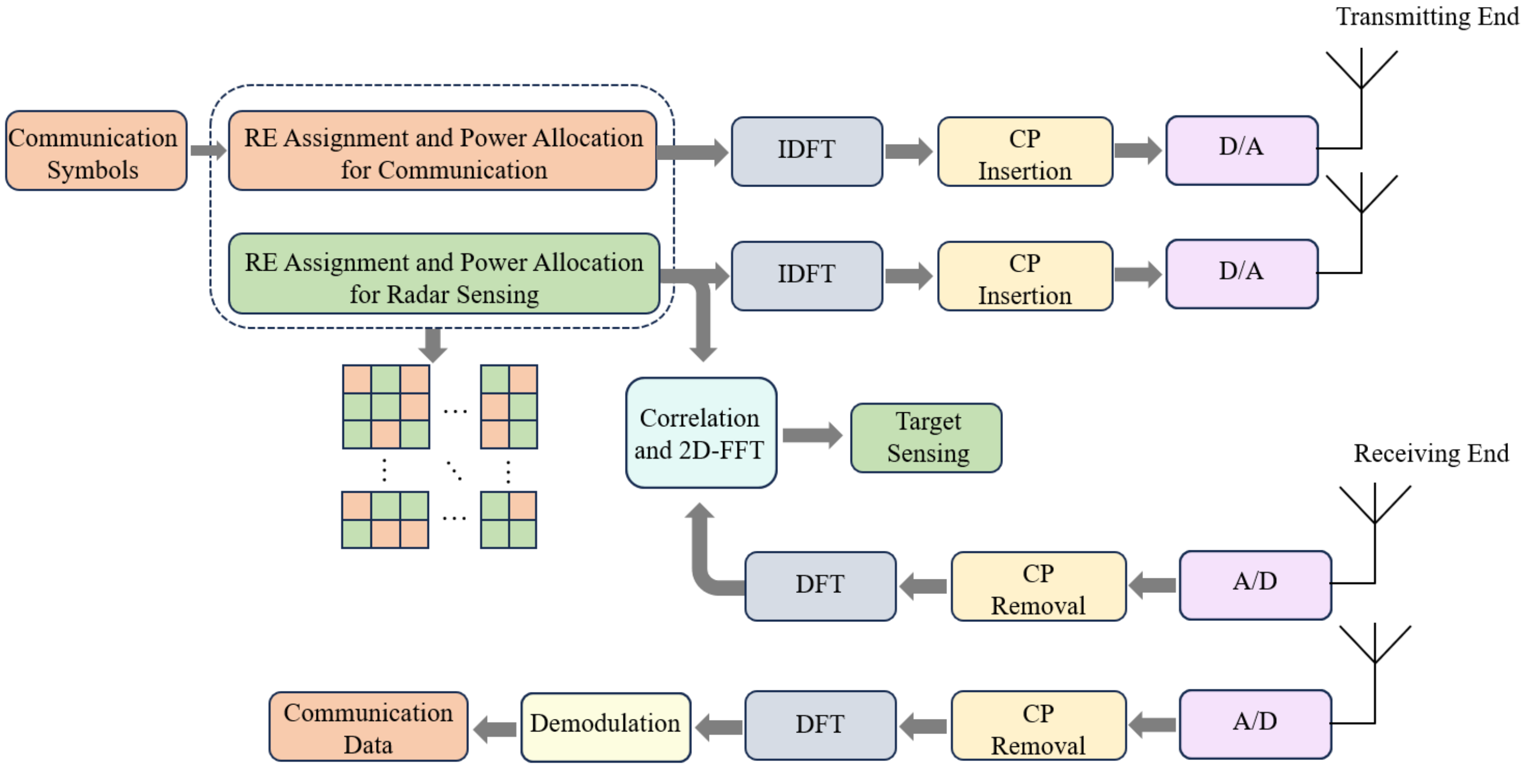
OFDM Resource Optimization

- **To satisfy the diverse requirements of communication/sensing, dual functions tend to be allocated with different resource elements (REs)**
- **Resource allocation is conducted across time-frequency, power, delay-doppler domains to enhance both peak-to-side lobe ratio (PSLR) and achievable data rate**



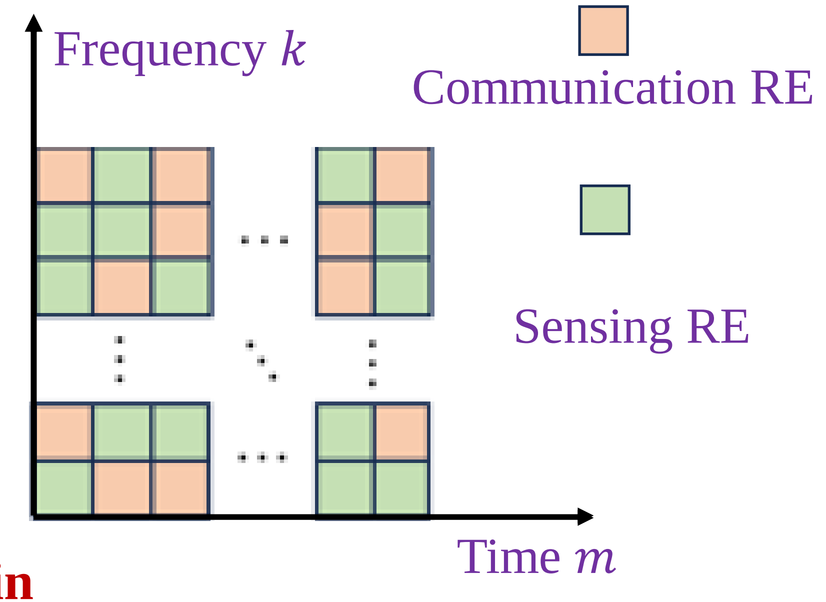
"Cross-Domain Dual-Functional OFDM Waveform Design for Accurate Sensing/Positioning" JSAC 2024

Performance Metrics

Signal model

$\boldsymbol{S} \in \mathbb{C}^{M\times K}$	Signal matrix
$S(m,k)$	Signal on the k-th subcarrier of the m-th OFDM symbol, i.e., (m,k)-th RE
$\boldsymbol{U} \in \mathbb{C}^{M\times K}$	Allocation of RE: $\begin{cases} U(m,k)=1, & \textbf{allocated to communication} \\ U(m,k)=0, & \textbf{allocated to sensing} \end{cases}$

- Sensing signal matrix $\boldsymbol{S}_r = \boldsymbol{U} \odot \boldsymbol{S}$, communication signal matrix $\boldsymbol{S}_c = (\boldsymbol{1} - \boldsymbol{U}) \odot \boldsymbol{S}$
- **$\odot$: Hadamard product; 1: all ones matrix;**
- **Power matrices of sensing/communications: $\boldsymbol{P}_r = |\boldsymbol{S}_r|^2$, $\boldsymbol{P}_c = |\boldsymbol{S}_c|^2$**



Performance metrics

- **Communication：achievable data rate**

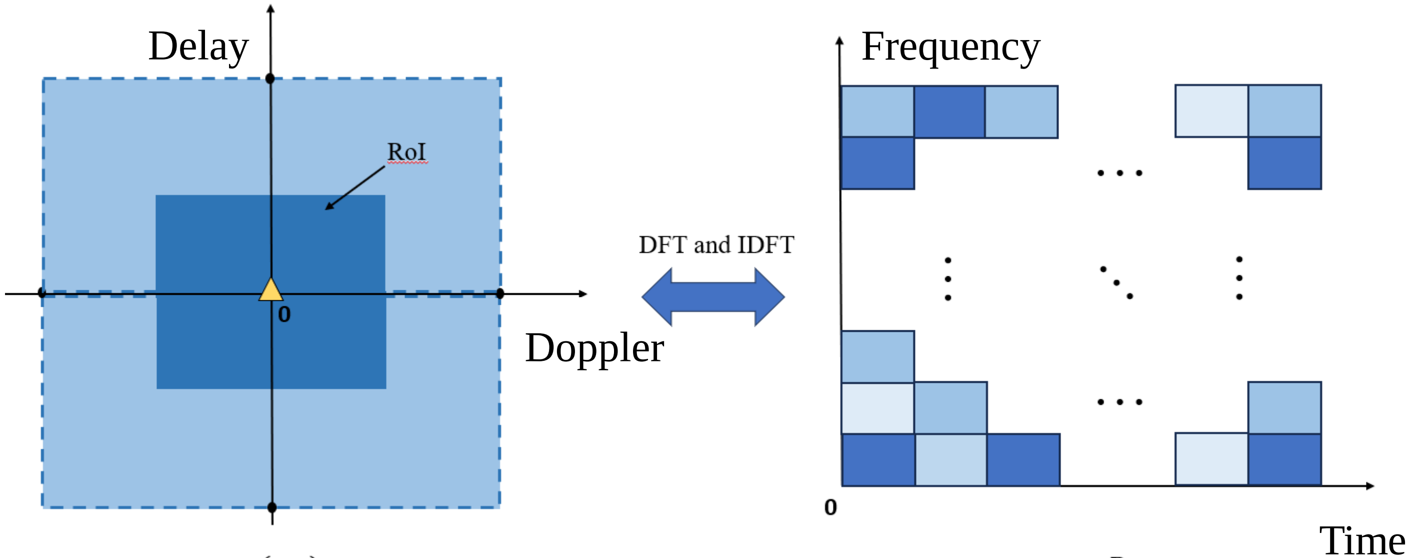
$$\sum_{m=0}^{M-1}\sum_{k=0}^{K-1}\log\left(1+\frac{P_c(m,k)|H_c(m,k)|^2}{\sigma^2}\right)$$

- **Sensing：PSLR in region of interest (RoI) of delay-doppler domain**

Cross-Domain OFDM Waveform Design

- **Sensing focus on delay-doppler domain to improve PSLR within RoI, where communication focus on time-frequency domain utilizing REs with favorable channel conditions**
- **Communication-centric waveform: assigns REs with good channel conditions for communication, then optimizes other RE powers for sensing to improve PSLR within RoI**
- **Sensing-centric waveform: guarantees the perfect autocorrelation property within ROI, then optimizes other delay-dollper domain values to improve the achievable data rate**

Relationship between delay-doppler domain and time-frequency domain

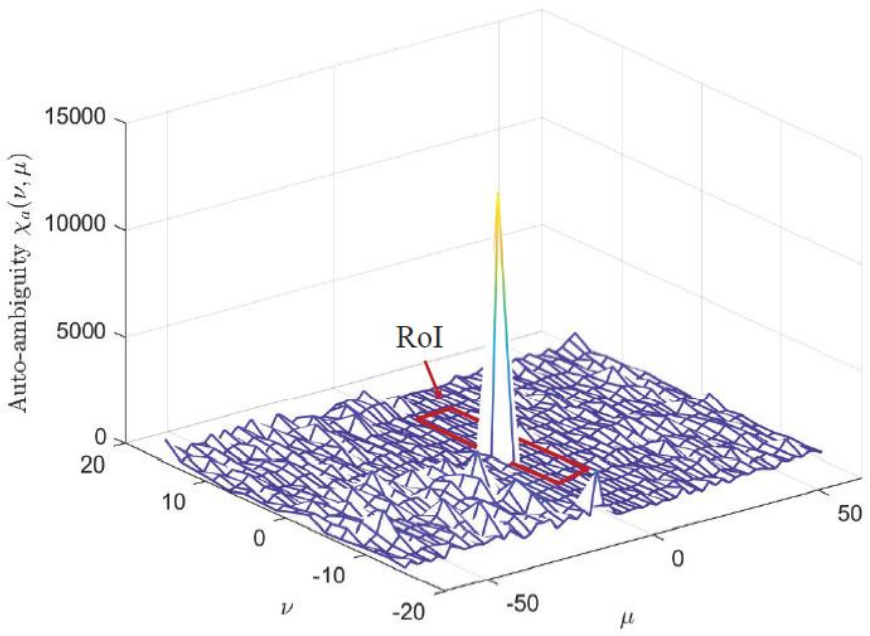


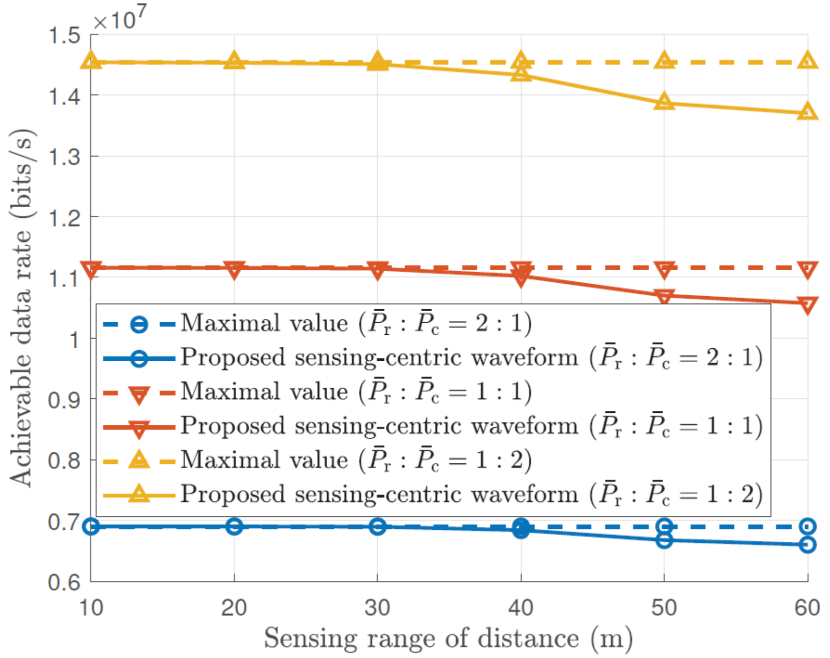
$\gamma(\nu,\mu)$
Delay-Doppler Domain

$\mathbf{P}_r$
Time-Frequency Domain

Simulation Results

- **The proposed communication-centric waveform maintains the optimal achievable data rate and exhibits good autocorrelation properties within RoI for sensing**
- **The proposed sensing-centric waveform approaches the optimal achievable data rate while ensuring the ‘locally’ perfect autocorrelation property**





Carrier frequency is 240 GHz, subcarrier spacing is 240 kHz. 32 consecutive OFDM symbols with 128 subcarriers are assumed, with each OFDM symbol having a length of 4.1470 μs and a cyclic prefix of 1.0368 μs.

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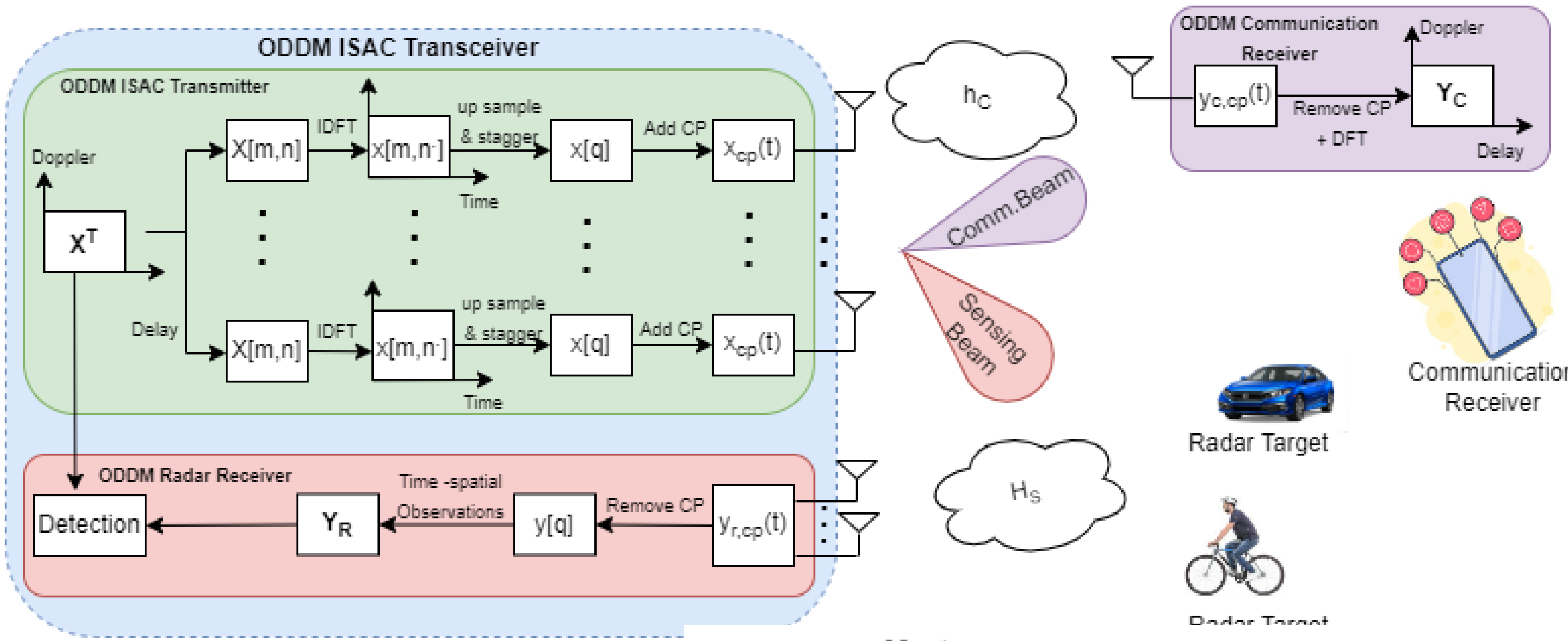
System Model



M - no. of subcarrier for symbol
N is no. of symbols for ODDM frame
m^{th} symbol
n^{th} subcarrier

- Time-domain discrete samples of the m-th ODDM symbol as

$$x[m,\dot{n}] = \sum_{n=0}^{N-1} X[m,n] e^{j2\pi \frac{\dot{n}n}{N}}, \dot{n} = 0, \dots N-1$$

Transmit symbols

- The received ODDM signal in time domain

$$y(t) = \sum_{q=-D_{\mathrm{CP}}}^{MN-1} x[q] \int_{\tau} a\left(t - qT_s - \tau\right) h(\tau, t) d\tau + z(t).$$

- ODDM symbols are staggered to form the transmitted samples {x[q]} of an ODDM frame

$$x[q] \triangleq \dot{x}\left[[q]_M, \left\lfloor \frac{q}{M} \right\rfloor \right], \quad 0 \le q \le MN-1$$

Sum-rate and Cramer-Rao Lower bound (CRLB)

- The received SINR per frame of the i^th^ downlink user

$$\gamma_i = \frac{P_i h_{ii}}{\sum_{j=1}^{K} P_j h_{ij} + \sigma^2}, i \neq j.$$

- The achievable sum-rate of the users

$$R_i(\mathbf{P}, \mathbf{n}) = \log_2\left(1 + \frac{P_i h_{ii}}{\sum_{j=1}^{K} P_j h_{ij} + \sigma^2}\right)$$

interference from the other user

- P_i is the power of the i^{th} user through the n^{th} channel.
- h is the channel gain.
- σ^2 denotes the additive white Gaussian noise

- The Cramer Rao lower bound (CRLB) is given as

$$\epsilon_{\theta_i}(\mathbf{P}, \mathbf{n}) := \operatorname{tr}\left(\mathsf{J}^{-1}(\theta_i)_{i,j}\right)$$

- Fisher information matrix of θ

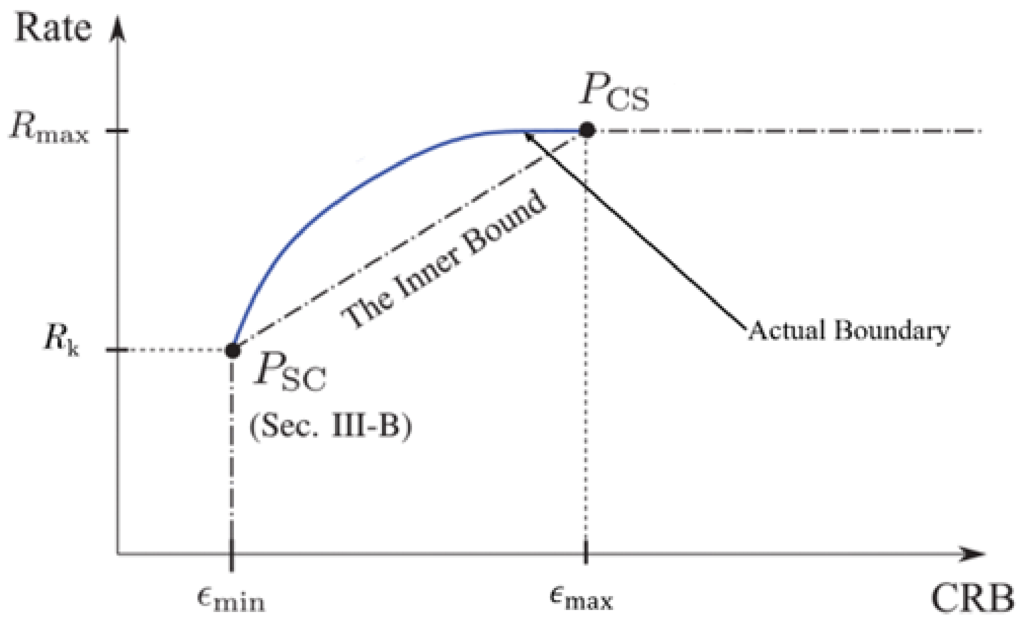
$$[\mathsf{J}(\theta_i)]_{i,j} = \frac{2\mathbf{P}_i}{\sigma^2}\Re\left[\sum_{m,n,t} \frac{\partial y'_{i,t}[m,n]^*}{\partial \theta_i} M_{Z\,i,j}^{-1} \frac{\partial y'_{i,t}[m,n]}{\partial \theta_j}\right]$$

- θ is the required parameters to be estimated
- M_Z is the covariance matrix of the noise Z

CRLB –Rate Region

- The inner bound of the CRLB-rate region are obtained by the pareto optimal and satisfies the below

$$\epsilon \geq \epsilon_{\min},$$
$$R \leq R_{\max},$$
$$\epsilon \geq \epsilon_{\min} + \frac{\epsilon_{\mathrm{CS}} - \epsilon_{\min}}{R_{\max} - R_{\mathrm{k}}}(R - R_{\mathrm{k}}),$$



where,

$$\epsilon_{\min}(\mathbf{P},\mathbf{n}) := \min_{p_{\mathbf{X}}(\boldsymbol{X})\in\mathcal{F}} \epsilon_{\theta_i}(\mathbf{P},\mathbf{n}), \quad \epsilon_{\mathrm{CS}} := \min_{p_{\mathbf{X}}(\boldsymbol{X})\in\mathcal{F}} \epsilon, \ \text{ s.t. } T^{-1}I(\mathbf{Y}_{\mathrm{DD}};\mathbf{X}|\mathbf{H}_{\mathrm{DD}}) = R_{\max},$$

$$R_{\max} := \max_{p_{\mathbf{X}}(\boldsymbol{X})\in\mathcal{F}} T^{-1}I(\mathbf{Y}_{\mathrm{DD}};\mathbf{X}|\mathbf{H}_{\mathrm{DD}}), \quad R_{\mathrm{k}} := \max_{p_{\mathbf{X}}(\boldsymbol{X})\in\mathcal{F}} T^{-1}I(\mathbf{Y}_{\mathrm{DD}};\mathbf{X}|\mathbf{H}_{\mathrm{DD}}), \ \text{ s.t. } \epsilon=\epsilon_{\min},$$

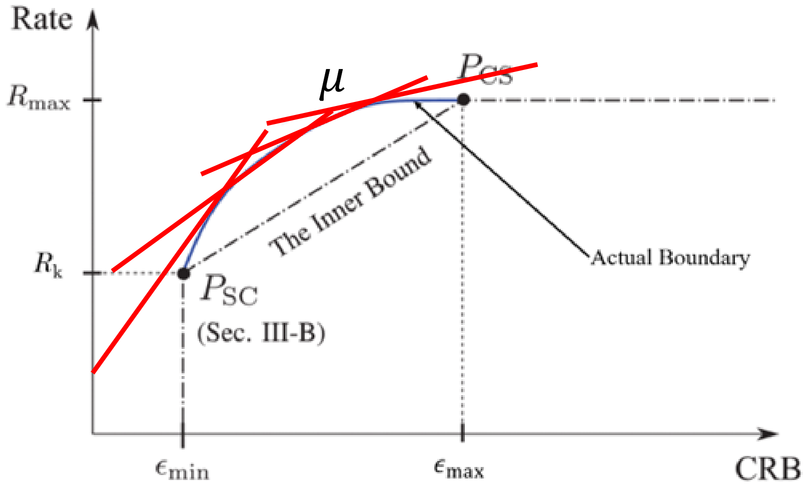
$$P_{\mathrm{SC}} := (\epsilon_{\min}, R_{\mathrm{k}}), \ P_{\mathrm{CS}} := (\epsilon_{\max}, R_{\max}).$$

Optimization Problem

- To obtain an optimal location for minimum CRLB and achievable sum-rate we defined an optimization problem as below

$$(\mathbf{P})\ \max_{\mathbf{P},\mathbf{n}} \left(-\frac{1}{K}\sum_{i=1}^{K} \epsilon_{\theta_i}(\mathbf{P},\mathbf{n}) + \mu \sum_{i=1}^{K} R_i(\mathbf{P},\mathbf{n}) \right),$$

$$\text{s.t.} \begin{cases} \frac{1}{K}\sum_{i=1}^{K} \epsilon_{\theta_i}(\mathbf{P},\mathbf{n}) \geq \epsilon_{min}, \\ \sum_{i=1}^{K} R_i(\mathbf{P},\mathbf{n}) \geq R_k, \end{cases}$$



- The optimization problem is decomposed as P.1 and P.2.

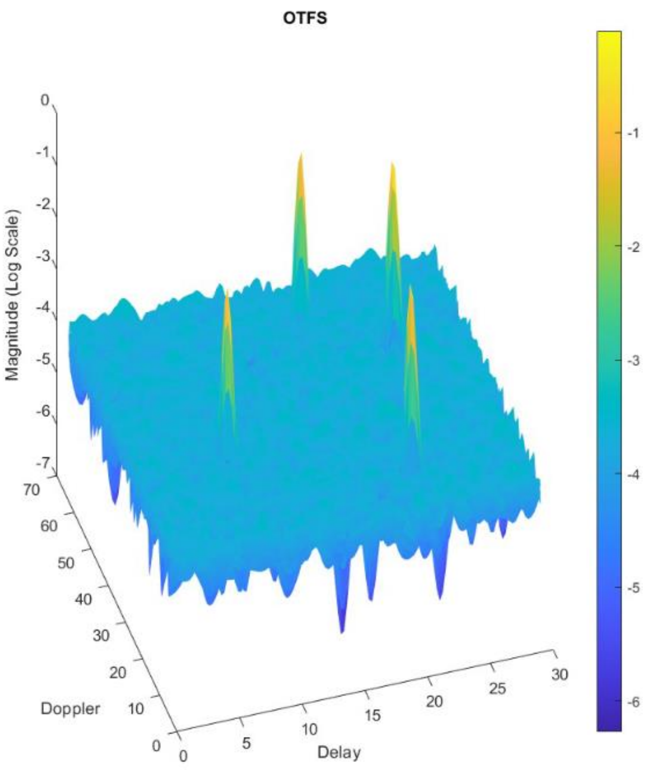
$$(\mathbf{P.1})\ \max_{\mathbf{P}} \left(\mu \sum_{i=1}^{K} R_i(\mathbf{P},\mathbf{n}) \right),$$

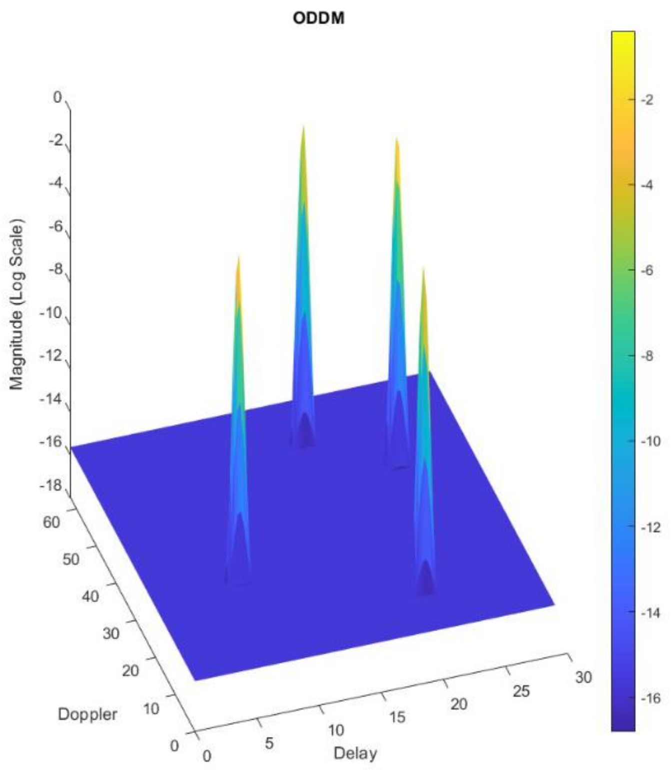
$$\text{s.t.} \begin{cases} \text{tr}\left(\boldsymbol{J}^{-1}\right) \leq \epsilon_{\max}, \\ \text{tr}(\boldsymbol{J}) \leq P. \end{cases}$$

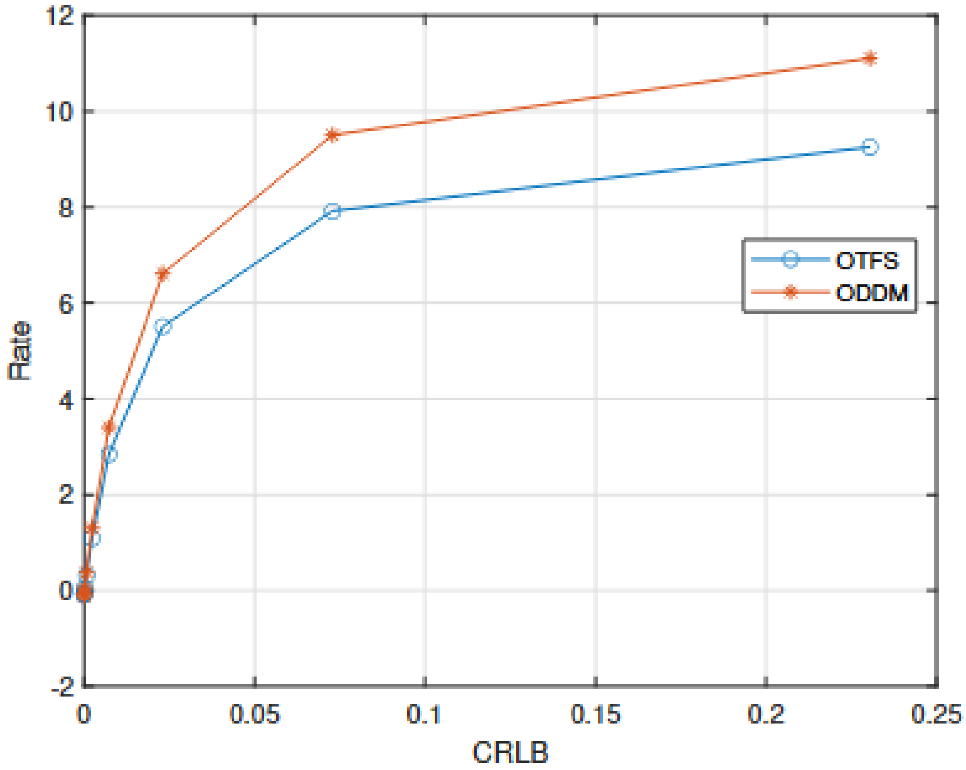
$$(\mathbf{P.2})\ \min_{\mathbf{P}} \left(\frac{1}{K}\sum_{i=1}^{K} \epsilon_{\theta_i}(\mathbf{P},\mathbf{n}) \right),$$

$$\text{s.t.} \begin{cases} R_i \leq R_{max}, \\ P_r \leq P_t - Pc. \end{cases}$$

Results







ODDM exhibits a more focused and sparse signal distribution with significantly lower interference levels compared to OTFS

ODDM offers the highest achievable rates across the range of CRLB values. Suitable for applications requiring high data rates with varying degrees of estimation precision.

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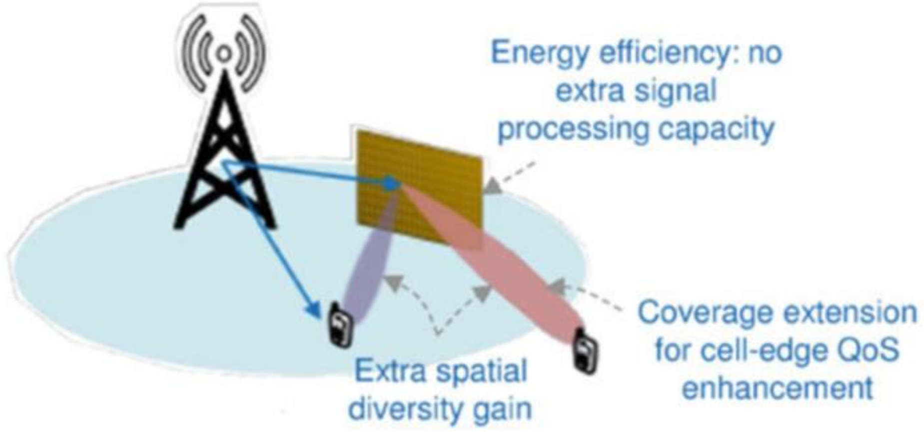
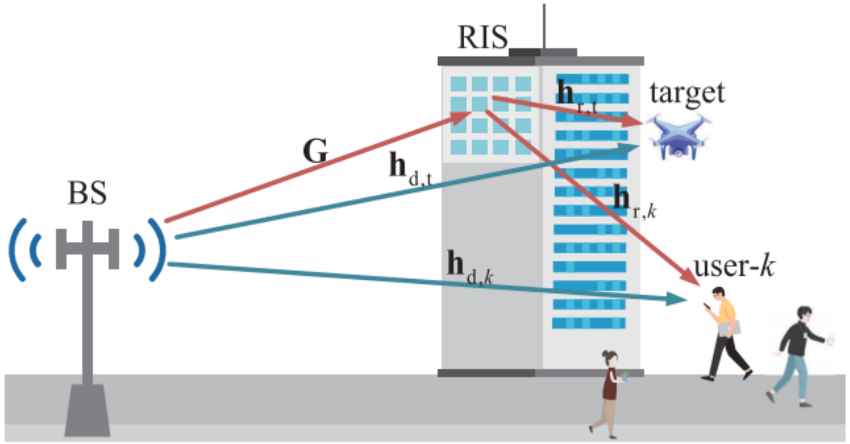
RIS-Aided ISAC Systems

- Reconfigurable Intelligent Surface (RIS)
  - **Improve Performance Metrics, e.g., SE, EE, Cell Coverage**



Applications of RISs for wireless communications

- RIS-Aided ISAC Systems
  - **Improve S&C Performance Metrics, e.g., SINR, CRLB**



Applications of RISs for wireless communications

Active Beamforming

Direct BS-User channel $\mathbf{H}_d$ **(Active)** BS-RIS-User channel $\mathbf{H}_R = \mathbf{G}\mathbf{\Phi}_R\mathbf{H}_I$ **(Passive)**

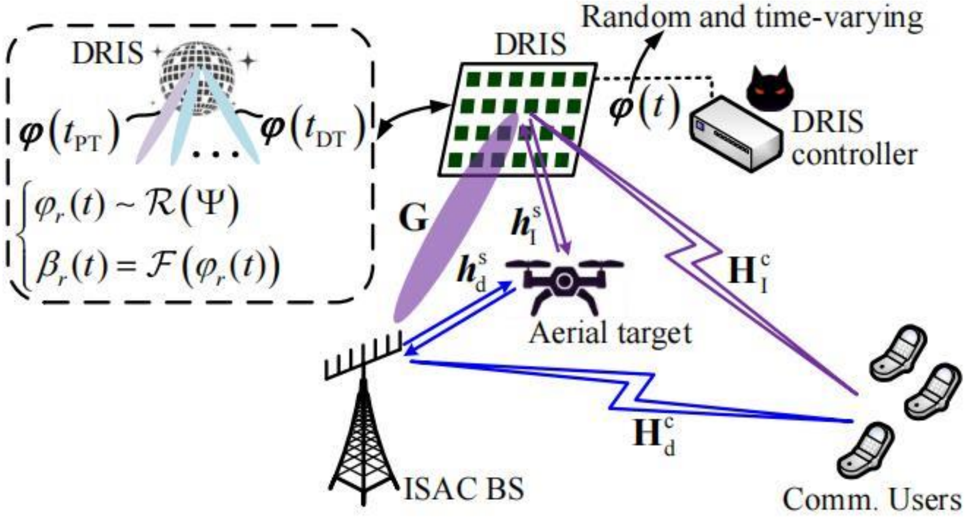
Passive Beamforming

Joint Active And Passive Beamforming Optimization Based On CSI

[1] Zhang H, Di B, Song L, et al., Reconfigurable Intelligent Surface-Empowered 6G[M]. Berlin/Heidelberg, Germany: Springer, 2021.
[2] R. Liu, M. Li, Q. Liu, A. L. Swindlehurst, “SNR/CRB-constrained joint beamforming and reflection designs for RIS-ISAC systems,” *IEEE Trans. Wireless Commun.*, vol. 23, no. 7, pp. 7456-7470, Jul. 2024.

Fully-Passive Jamming in ISAC

- DISCO Reconfigurable Intelligent Surface (DRIS)
- **Reduce Sensing And Communication performance Simultaneously**



Downlink of an ISAC system jammed by a DRIS-based FPJ

What's the impact of illegitimate RISs on an ISAC system?

$$\gamma_k = \mathrm{E}\left[\frac{\left|s_{k,l}\right|^2}{\left|\left(\left(\boldsymbol{h}_{\mathrm{PT},k}^{\mathrm{c}}\right)^* \boldsymbol{x}_l - s_{k,l}\right) + \left(\boldsymbol{h}_{\mathrm{ACA},k}^{\mathrm{c}}\right)^* \boldsymbol{x}_l\right|^2 + \sigma_{\mathrm{c}}^2}\right]$$

$$\begin{cases} \mathbf{X}_0 \Rightarrow \frac{\mathbf{X}_0\mathbf{X}_0^*}{L} = \frac{P_0}{N}\mathbf{I}_N \\ (1-\rho)\left\|\mathbf{X}-\mathbf{X}_0\right\|_{\mathrm{F}}^2, 0 \le \rho \le 1 \end{cases}$$

A **Pareto optimization** problem with **a tradeoff factor ρ** to balance the performance between S&C functions

Design **X**

Received Communication Symbols

$$\mathbf{Y}_{\mathrm{c}} = \mathbf{S} + \underbrace{\left(\mathbf{H}_{\mathrm{PT}}^{\mathrm{c}}\mathbf{X} - \mathbf{S}\right)}_{\text{MUI}} + \underbrace{\mathbf{H}_{\mathrm{ACA}}^{\mathrm{c}}\mathbf{X}}_{\text{ACAI}} + \mathbf{N}_{\mathrm{c}}$$

Received Sensing Symbols

$$\mathbf{Y}_{\mathrm{s}} = \kappa\left(\boldsymbol{h}_{\mathrm{d}}^{\mathrm{s}} + \boldsymbol{h}_{\mathrm{D}}^{\mathrm{s}}(t)\right)\left(\boldsymbol{h}_{\mathrm{d}}^{\mathrm{s}} + \boldsymbol{h}_{\mathrm{D}}^{\mathrm{s}}(t)\right)^* \mathbf{X} + \mathbf{N}_{\mathrm{s}}$$

$$\min_{\mathbf{X}} \rho\left\|\mathbf{H}_{\mathrm{PT}}^{\mathrm{c}}\mathbf{X} - \mathbf{S}\right\|_{\mathrm{F}}^2 + (1-\rho)\left\|\mathbf{X}-\mathbf{X}_0\right\|_{\mathrm{F}}^2$$
$$\text{s.t. } \operatorname{tr}\left(\mathbf{X}\mathbf{X}^*\right) = P_0 L$$

[3] H. Huang, H. Zhang, W. Mei, J. Li, Y. Cai, A. L. Swindlehurst, Z. Han, "Integrated sensing and communication under DISCO physical-layer jamming attacks," IEEE Wireless Commun. Lett., vol. 13, no. 11, pp. 3044-3048, Nov. 2024.

Fully-Passive Jamming in ISAC

- Impact of DISCO RIS on An ISAC System

- **Active Channel Aging in Sensing and Communication**

$$\min_{\mathbf{X}} \rho \left\| \mathbf{H}_{\mathrm{PT}}^{\mathrm{c}} \mathbf{X} - \mathbf{S} \right\|_{\mathrm{F}}^{2} + (1-\rho) \left\| \mathbf{X} - \mathbf{X}_0 \right\|_{\mathrm{F}}^{2}$$

$$\text{s.t. } \operatorname{tr}\left(\mathbf{X}\mathbf{X}^*\right) = P_0 L$$

Optimize **X** from the Pareto optimization problem

Received Communication Symbols

$$\mathbf{Y}_{\mathrm{c}} = \mathbf{S} + \underbrace{\left(\mathbf{H}_{\mathrm{PT}}^{\mathrm{c}} \mathbf{X} - \mathbf{S}\right)}_{\mathrm{MUI}} + \underbrace{\mathbf{H}_{\mathrm{ACA}}^{\mathrm{c}} \mathbf{X}}_{\mathrm{ACAI}} + \mathbf{N}_{\mathrm{c}}$$

ACA Interference

Received Sensing Symbols

$$\mathbf{Y}_{\mathrm{s}} = \kappa \left(\boldsymbol{h}_{\mathrm{d}}^{\mathrm{s}} + \boldsymbol{h}_{\mathrm{D}}^{\mathrm{s}}(t) \right) \left(\boldsymbol{h}_{\mathrm{d}}^{\mathrm{s}} + \boldsymbol{h}_{\mathrm{D}}^{\mathrm{s}}(t) \right)^* \mathbf{X} + \mathbf{N}_{\mathrm{s}}$$

Time-Varying DRIS-Jammed Channel

Communication Performance

$$\gamma_k = \mathrm{E}\left[\frac{\left|s_{k,l}\right|^2}{\left| \left(\left(\boldsymbol{h}_{\mathrm{PT},k}^{\mathrm{c}}\right)^* \boldsymbol{x}_l - s_{k,l} \right) + \left(\boldsymbol{h}_{\mathrm{ACA},k}^{\mathrm{c}}\right)^* \boldsymbol{x}_l \right|^2 + \sigma_{\mathrm{c}}^2} \right]$$

Proposition 1: The elements of $\mathbf{H}_{\mathrm{ACA}}^{\mathrm{c}}$ converge in distribution to $\mathcal{CN}(0, \mathscr{L}_{\mathrm{cas},k} N_{\mathrm{D}} \overline{\mu})$ as $N_{\mathrm{D}} \to \infty$, i.e.,

$$[\mathbf{H}_{\mathrm{ACA}}^{\mathrm{c}}]_{n,k} \xrightarrow{\mathrm{d}} \mathcal{CN}(0, \mathscr{L}_{\mathrm{cas},k}^{\mathrm{c}} N_{\mathrm{D}} \overline{\mu}), \forall n, k,$$

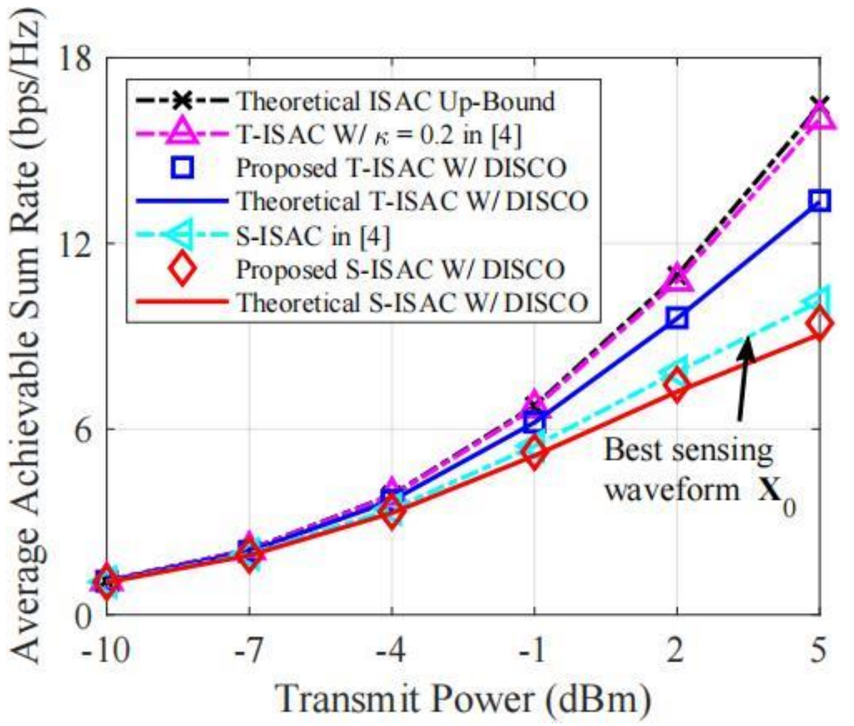
Sensing Performance

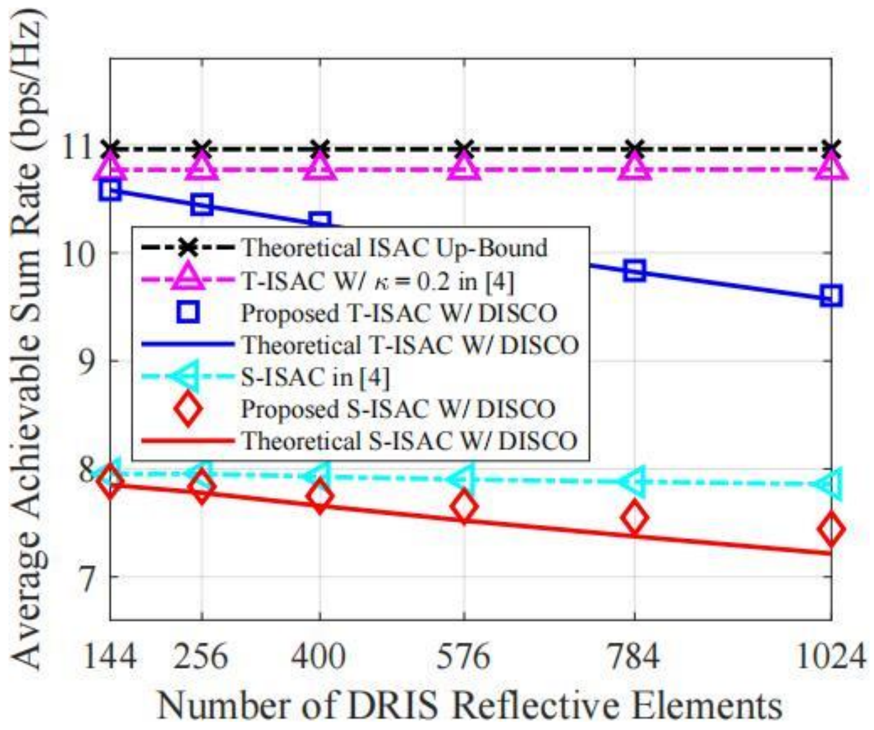
Proposition 2: The i.i.d. elements of $\boldsymbol{h}_{\mathrm{D}}^{\mathrm{s}}(t)$ converge in distribution to $\mathcal{CN}(0, \mathscr{L}_{\mathrm{cas}}^{\mathrm{s}} N_{\mathrm{D}} \overline{\nu})$ as $N_{\mathrm{D}} \to \infty$, i.e.,

$$h_{\mathrm{D},n}^{\mathrm{s}}(t) \xrightarrow{\mathrm{d}} \mathcal{CN}(0, \mathscr{L}_{\mathrm{cas}}^{\mathrm{s}} N_{\mathrm{D}} \overline{\nu}), n = 1, \cdots, N_{\mathrm{B}},$$

[3] H. Huang, H. Zhang, W. Mei, J. Li, Y. Cai, A. L. Swindlehurst, Z. Han, "Integrated sensing and communication under DISCO physical-layer jamming attacks," IEEE Wireless Commun. Lett., vol. 13, no. 11, pp. 3044-3048, Nov. 2024.

Some Conclusions





- The sum rate is not seriously affected by the sensing functionality when the ISAC waveform is well designed;
- The performance is severely compromised by DRIS-based DISCO jamming attacks without any knowledge of the DRIS-jammed channels;
- The impact of DISCO jamming attacks on the sum rate can be quantified by the statistical characteristic of ACA interference.

Outline

- **Motivation for ISAC**
  - Fundamental
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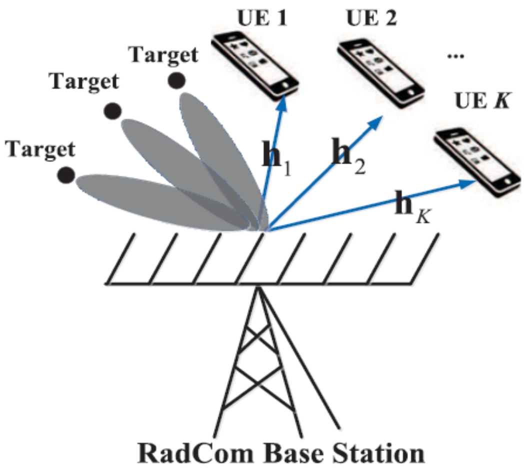
iSAC
EMERGING TECHNOLOGY INITIATIVE

ISAC+ High Speed Train (HSR) Motivation

ISAC+HSR

Intelligent high-speed rail requires a new integrated sensing and communication system that balances two functions, optimizes resource integration, enhances communication stability and data rate, and improves the accuracy and responsiveness of environmental sensing, to meet the demands for reliability and precision in high-speed scenarios.

- High-Speed Wireless Communication Support and Assurance.
- Environmental Sensing and Monitoring during Construction Phase.
- Environmental Monitoring and Management during Operation Phase.



Challenge

Transmission mechanism design

1. **Trade-off between sensing-communication performance.**

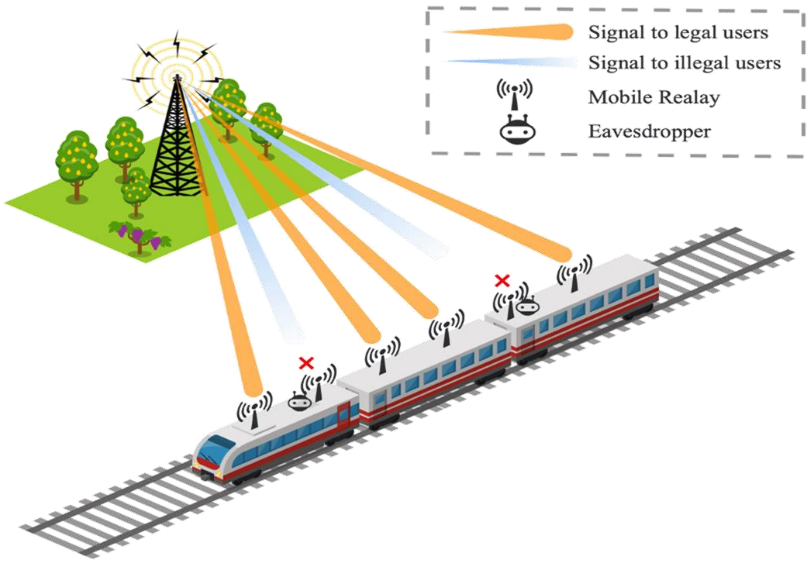
System parameter optimization

2. **High loss and blockage to blockage in mmWave.**

Low-complexity algorithm design

3. **Resource coupling between sensing and communication.**

System Model



Functional Objectives

- **Coverage Expansion**: Utilize ISAC to improve mmWave communication coverage and reduce signal blockage.
- **Resource Optimization**: Optimize power allocation and waveform design to maximize system performance.

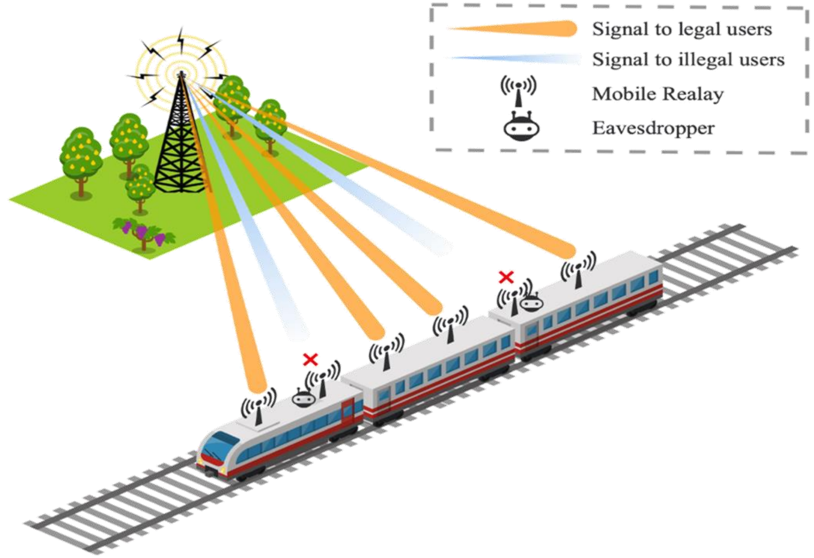
System Components

- **ISAC BS**: Integrated sensing and communication base station with beamforming capabilities.
- **Mobile Relays (MRs)**: Rooftop devices on train carriages aiding secure communication and data distribution.

Parameter Optimization

1. **Transmit Beamforming Matrix** $\boldsymbol{W}$: Optimizes signal directionality to legitimate MRs.
2. **ISAC Waveform Design** $\boldsymbol{X}$: Enhances communication performance while maintaining blind zones for eavesdroppers.

Problem Formulation



Solution Approach

- **Challenges**: Non-convex constraints and coupled variables.
- **Algorithm**: Decompose the optimization problem into two subproblems
  ① **Beamforming Optimization**: Optimize ***W*** using SCA algorithm.
  ② **Waveform Design**: Optimize ***X*** with constant modulus constraints.

Optimization

Objective: Maximizing communication sum rate

$$(P1) \quad \max_{\mathbf{W},\mathbf{X}} \sum_{k\in\mathcal{K}\setminus\mathcal{L}} \log_2(1+\gamma_k)$$

$$\|\mathbf{W}\|_F^2 \le P_T,$$

Transmission Power Constraint

$$|x_{i,j}| = \frac{1}{\sqrt{N_t}}, \forall i, j.$$

Constant Modulus Constraint

Sensing SINR Constraint

$$Tr\left[\mathbf{X}^H\mathbf{W}^H\widetilde{\mathbf{A}}_k^H\mathbf{R}_N^{-1}\widetilde{\mathbf{A}}_k\mathbf{W}\mathbf{X}\right] \ge \frac{1}{2|\xi_k|^2\eta}, \forall k\in\mathcal{K}\setminus\mathcal{L}.$$

Blind Region Constraint

$$\sum_{l\in\mathcal{L}} \int_{-s_{th}}^{s_{th}} \left\|\mathbf{B}^H\mathbf{H}_k\mathbf{W}\mathbf{X}\right\|_F^2 ds \le \psi.$$

Proposed Solution

Solution Approach

1. The Lower Bound of (P1) :
   - **Objective Simplification**: Using SCA, the logarithmic terms are approximated linearly to derive a lower bound:

$$\log_2(1+\gamma_k) \approx \frac{\gamma_k - \gamma_k^{(i)}}{\ln(2)(1+\gamma_k^{(i)})}.$$

   - **Constraint Relaxation**: Non-convex constraints are transformed into convex form using SCA and auxiliary variables.

$$\gamma_k \geq \frac{1}{2|\xi_k|^2\eta}.$$

$$1/N_t - 2\,\mathrm{Re}(x_{i,j}x_{i,j}^{(n)}) + |x_{i,j}^{(n)}|^2 \leq 0, \quad \forall i,j.$$

2. **Reformulated Problem**
3. **Decoupling Variables**
4. **Iterative Solution**

Algorithm Workflow

1. **Input**: System parameters
   $P_T, CRB\ threshold\ \eta, blind\ region\ threshold\ \psi$
2. Iterative steps:
   - Optimize $\boldsymbol{W}$ for fixed $\mathbf{X}$:
     - solve:

$$\max_{\boldsymbol{W}} \sum_{\boldsymbol{k}\in\boldsymbol{K}\backslash \mathrm{L}} \log_2(1+\gamma_k)$$

   - Optimize $\mathbf{X}$ for fixed $\boldsymbol{W}$:
     - solve:

$$\sum_{\boldsymbol{k}\in\boldsymbol{K}\backslash \mathrm{L}} \log_2(1+\gamma_k)$$

3. Convergence Criteria:
   - Alternate between W and X until:

$$\left|R^{(i+1)} - R^{(i)}\right| \leq \epsilon$$

4. Output: Optimized $\boldsymbol{W}^*, \boldsymbol{\Phi}^*$

Simulation Results

Simulation Analysis

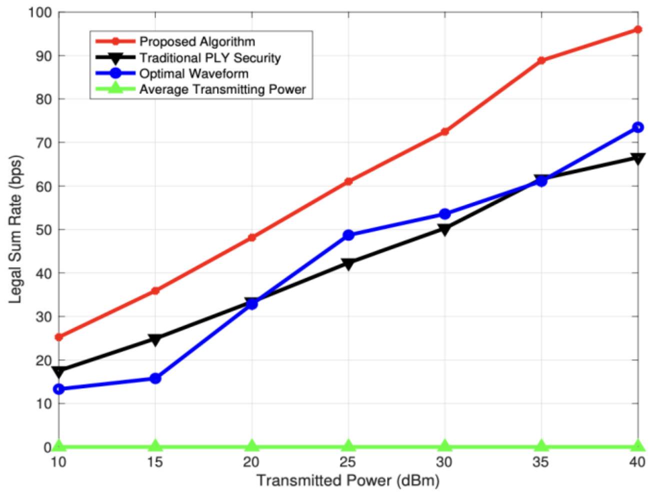


Fig. 3: The number of completed flows vs. the duration of time slot segent.

As the quantity of RIS components increases, the communication sum rate for all three RIS schemes increases. However, the rate of increase slows down with more elements. This is due to physical constraints like transmission power and Shannon capacity, showing diminishing returns after a certain number of RIS elements.

Simulation Analysis

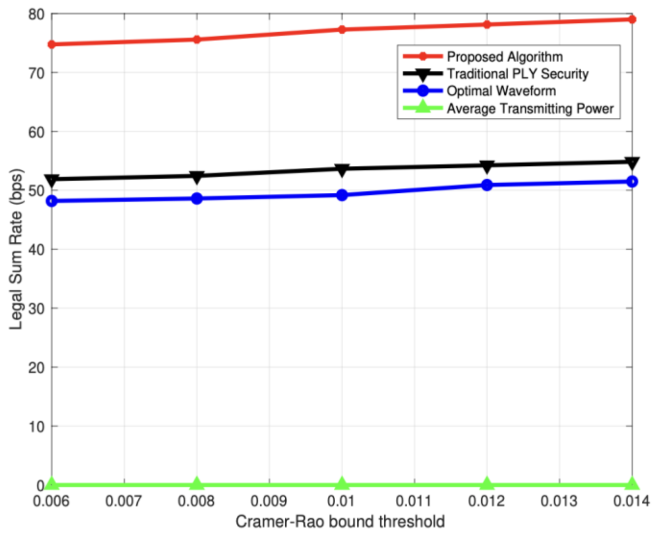


Fig. 4: The number of completed flows vs. the number of transmission time slots.

Both the proposed scheme and the APT algorithm show stable sum rates with increasing quantization bits, while the RPS scheme exhibits large fluctuations. This is because the proposed and APT algorithms optimize RIS phase shifts, ensuring more stable and higher performance, while RPS selects phase shifts randomly.

Panpan Li, Yong Niu, Hao Wu, Zhu Han, Ning Wang, Lei Xiong, Bo Ai, and Chau Yuen, “Secure High-Speed Train-to-Ground Communications Through ISAC,” IEEE Internet of Things Journal, vol. 11, no. 19, pp. 31235 - 31248, October 2024.
Yuanyuan Qiao, Yong Niu, Zhu Han, Ke Xiong, Ning Wang, Tony Quec, and Bo Ai, “Resource Allocation for ISAC and HRLLC in UAV-Assisted HSR System With a Hybrid PSO-Genetic Algorithm,” to appear IEEE Internet of Things Journal.

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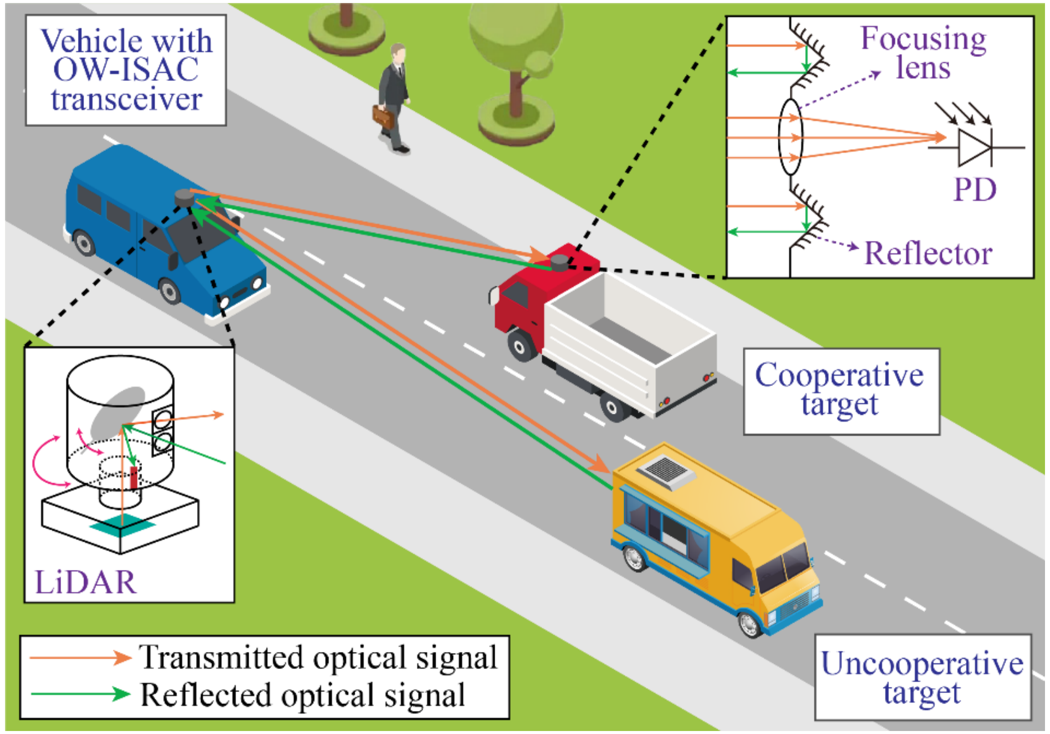
Free Space Optical (FSO) + ISAC

FSO-ISAC

- Similarities between free space optical (**FSO**) sensing and communication.
- Implemented on optical sensors like light detection and ranging (LiDAR). [Suzuki'15]
- High-precision sensing and high-capacity communication simultaneously.
- A complement to radio frequency (RF).



Research Gap

- Most of the existing FSO-ISAC schemes focus on pulses or single-carrier waveforms, with limited attention paid to **multi-carrier** waveforms like **OFDM**.
- What is the optimal DC bias for intensity modulation and direct detection (IM/DD)-based FSO-ISAC? *(Note that illumination is not always necessary for FSO-ISAC.)* Should we always avoid non-negative distortion?

Problem Formulation

Our Contributions

- A direct-current-biased (**DCO)-OFDM**-based **FSO-ISAC** scheme compatible with IM/DD.
- A joint optimization problem of DC bias and subcarrier power allocation.
- An iterative optimization algorithm to obtain the optimal dual variables in the closed-form expression of power allocation.

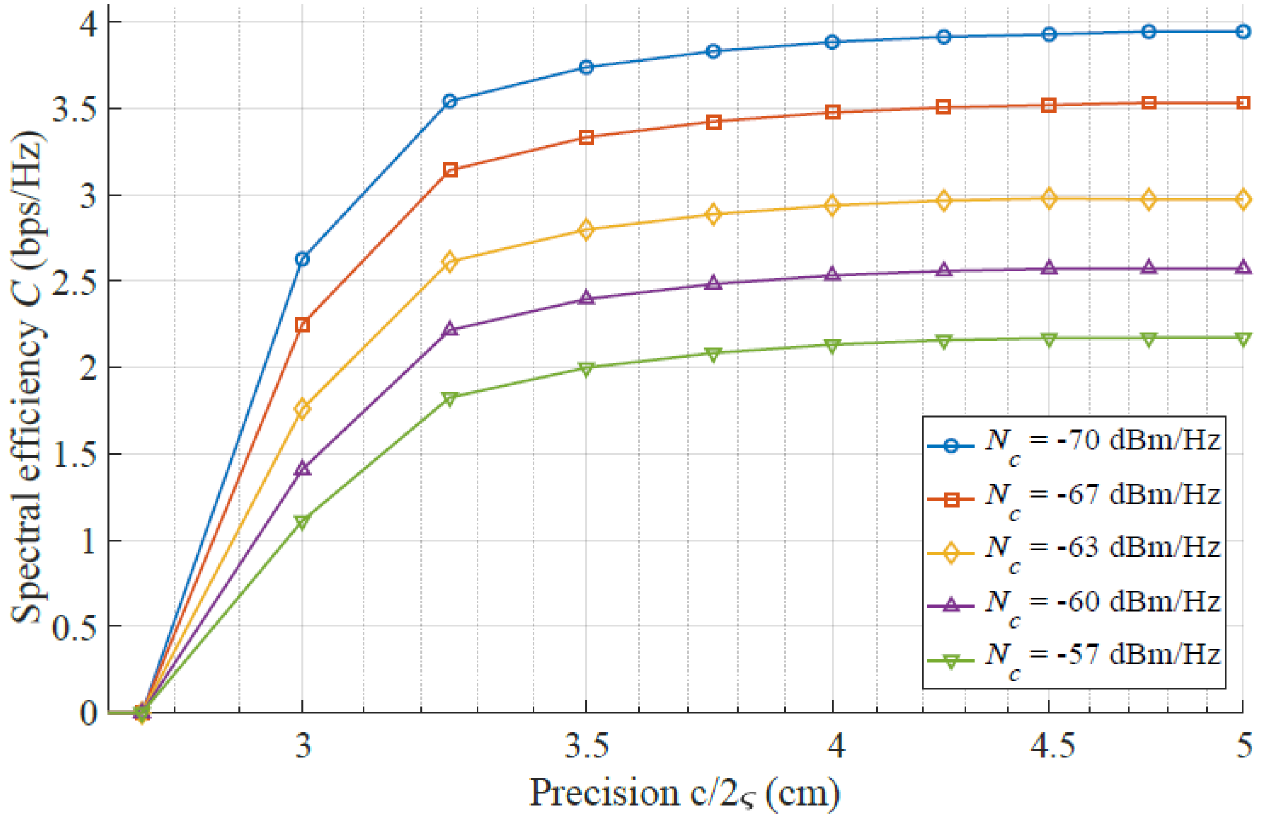
$$
\begin{aligned}
\max_{b,\tilde{P}(k)} \quad & C\left(b, \tilde{P}\left(k\right)\right) \\
\text{s.t.} \quad & I\left(b, \tilde{P}\left(k\right)\right) \geq \varsigma^2, \\
& 0 \leq b \leq \sqrt{P}, \\
& 0 \leq \tilde{P}\left(k\right) \leq P_m, \\
& \sum_{k=1}^{\frac{N}{2}-1} \tilde{P}\left(k\right) = \frac{1}{2},
\end{aligned}
$$

- $\max_{b,\tilde{P}(k)}$: Joint optimization of DC bias and subcarrier power.
- $C\left(b, \tilde{P}(k)\right)$: Communication performance metric as the objective.
- $I\left(b, \tilde{P}(k)\right) \geq \varsigma^2$: Sensing performance metric as a constraint. The desired sensing precision is $c/2\varsigma$.
- $0 \leq b \leq \sqrt{P}$, $0 \leq \tilde{P}(k) \leq P_m$: Non-negative and maximum-power constraints. We assume $P_m < \frac{1}{2} < \left(\frac{N}{2} - 1\right) P_m$ to avoid invalid constraint.
- $\sum_{k=1}^{\frac{N}{2}-1} \tilde{P}(k) = \frac{1}{2}$: Total power constraint.

Simulation Results

☐ Spectral efficiency V.S. Precision

- The proposed FSO-ISAC system cannot achieve optimal communication and sensing performances simultaneously. A trade-off exists between spectral efficiency and precision.
- Both communication and sensing performance metrics are **marginal**. One may become saturate while the other deteriorates drastically.



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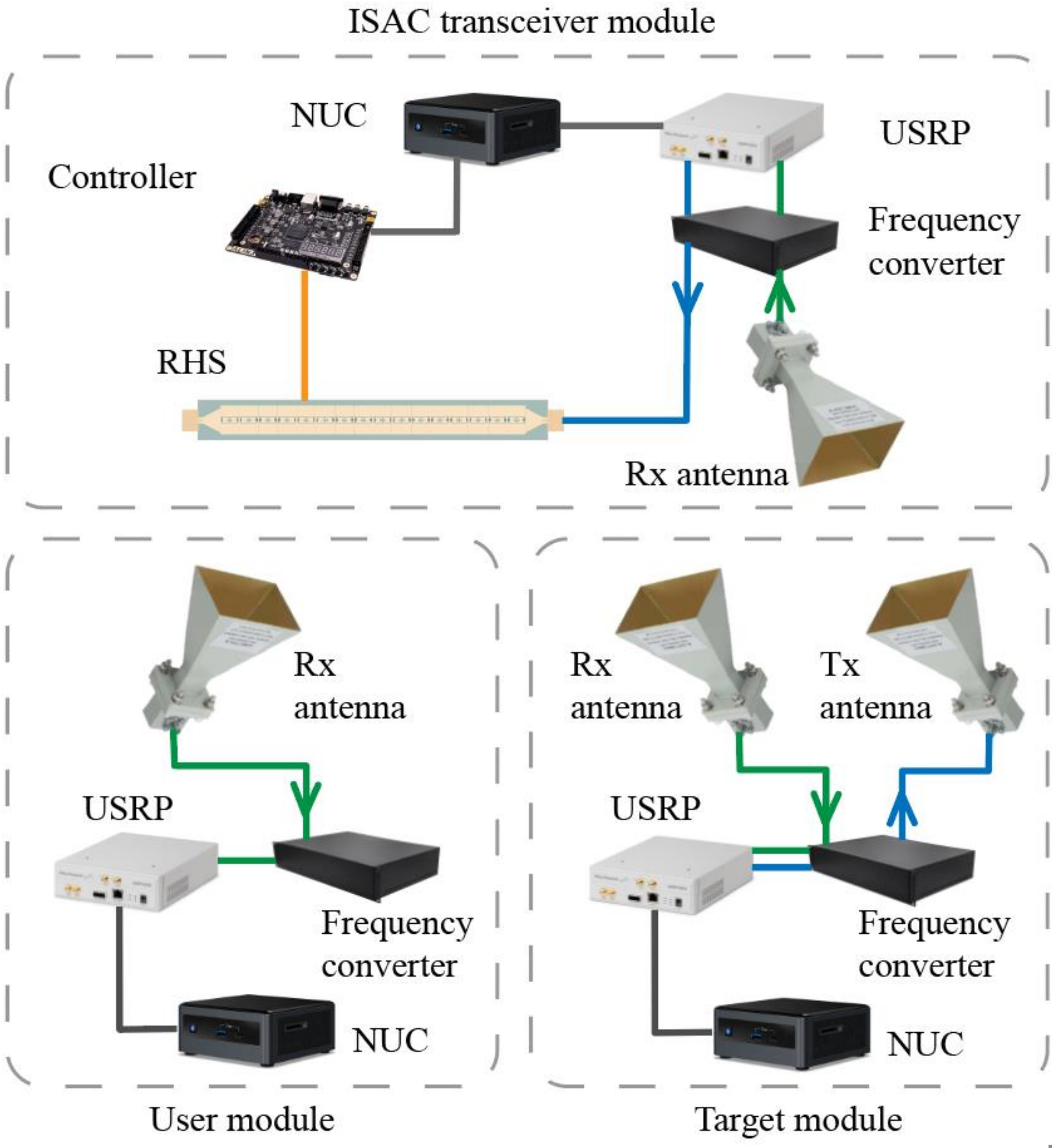
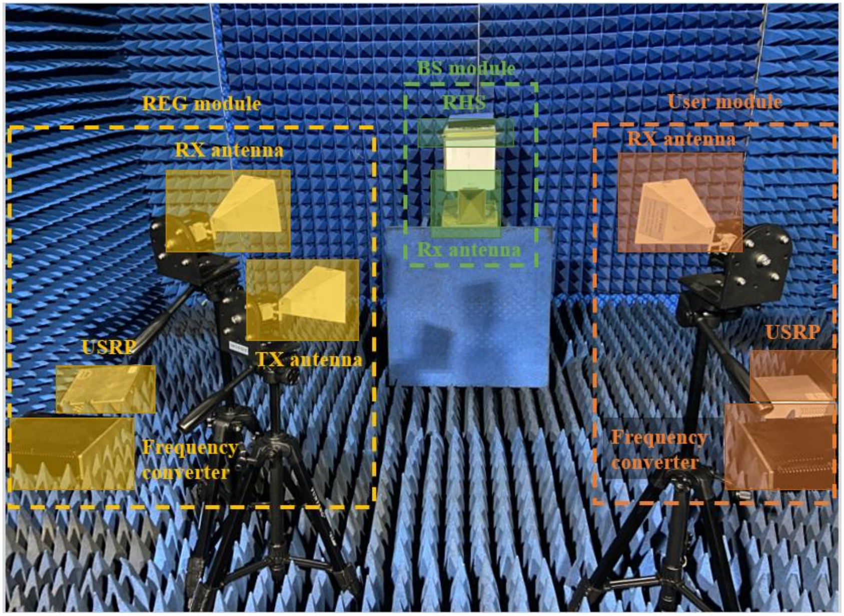
Demo 1: Reconfigurable Holographic Surface-aided ISAC

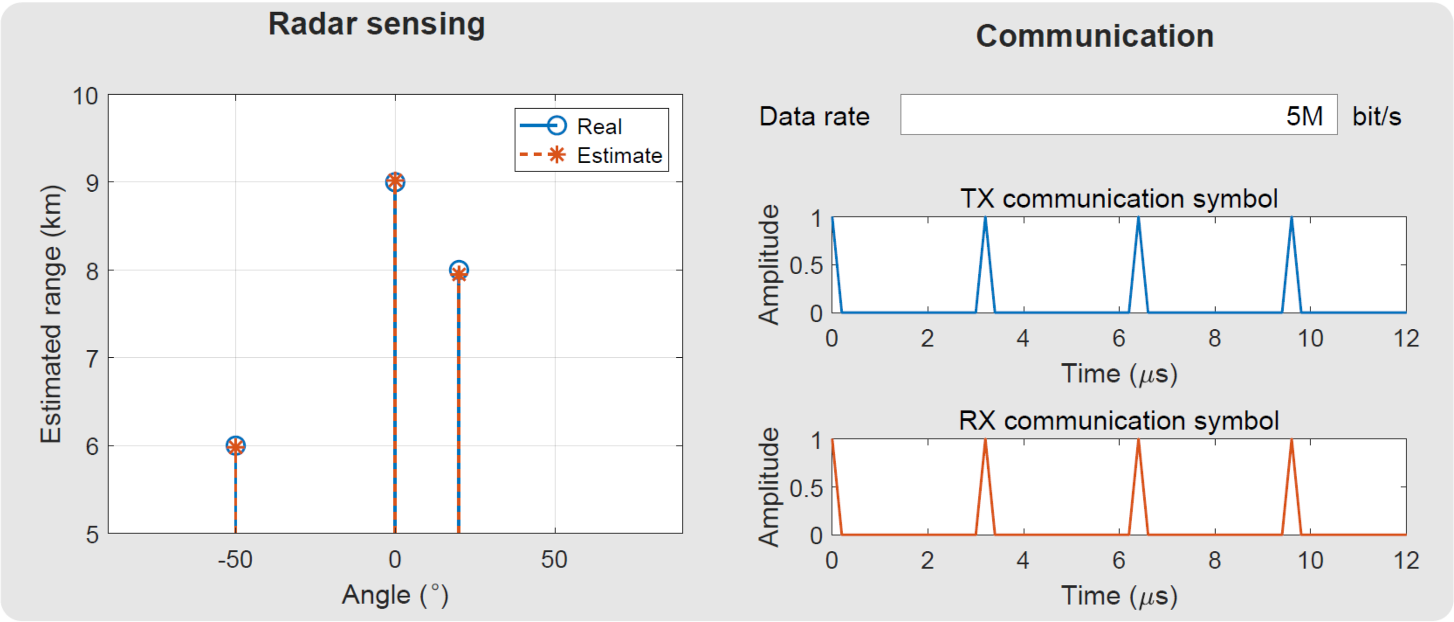
- **ISAC transceiver module**
  - Transmits ISAC signals and receives echo signals for radar detection
  - Components:
    - Intel NUC as the host computer
    - FPGA-based controller for RHS
    - USRP and frequency converter
    - Tx antenna: RHS
    - Rx antenna: horn antenna
- **User module**
  - Receives and decodes the ISAC signals to retrieve the communication stream.
- **Target module**
  - Simulates radar targets by generating controllable radar echo signals.



Experimental Results

- **Experiment setting:** anechoic chamber with a size of $4 \times 4 \times 2.5m^3$.
- **Radar sensing**: one of the main lobes of the radiation pattern is steered towards the direction of the target ($-50°, 0°$, or $20°$), and the estimated range is close to the real range.
- **Communication**: the other main lobe of the radiation pattern points towards the direction of the user and is able to support real-time data transmission.



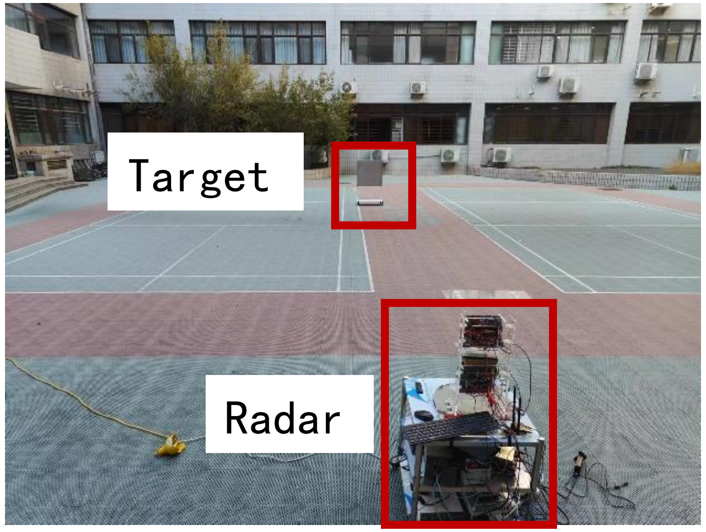


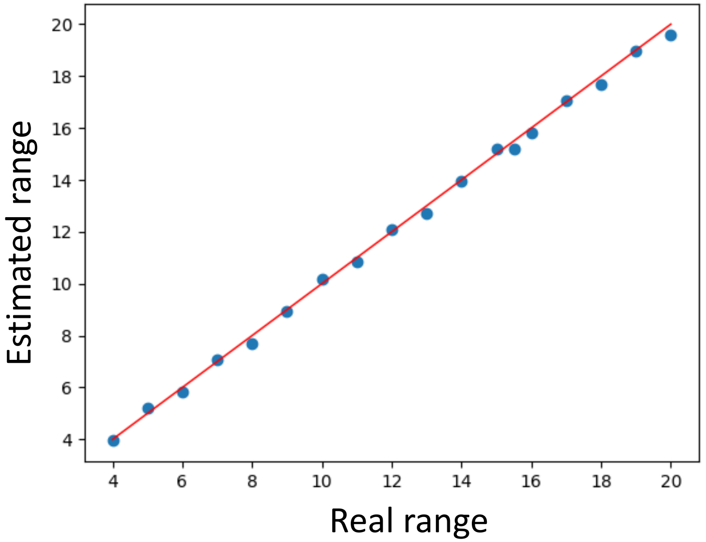
"A Reconfigurable Holographic Surface Enabled Energy Efficient mmWave Ultra-Massive MIMO Communication System," IEEE/CIC ICCC 2024, Best Demo Award

Experimental Results on RHS Radar

Range measurement

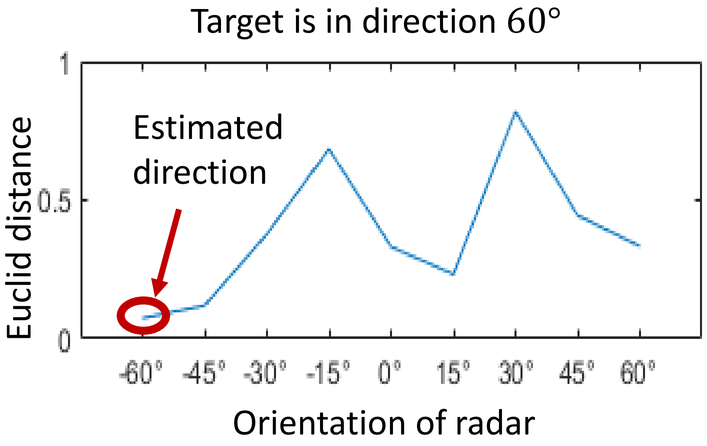
- Scenario: outdoor
- Radar target: metal plate
- Detection range: $[4, 21]m$
- Range accuracy: $0.425m$



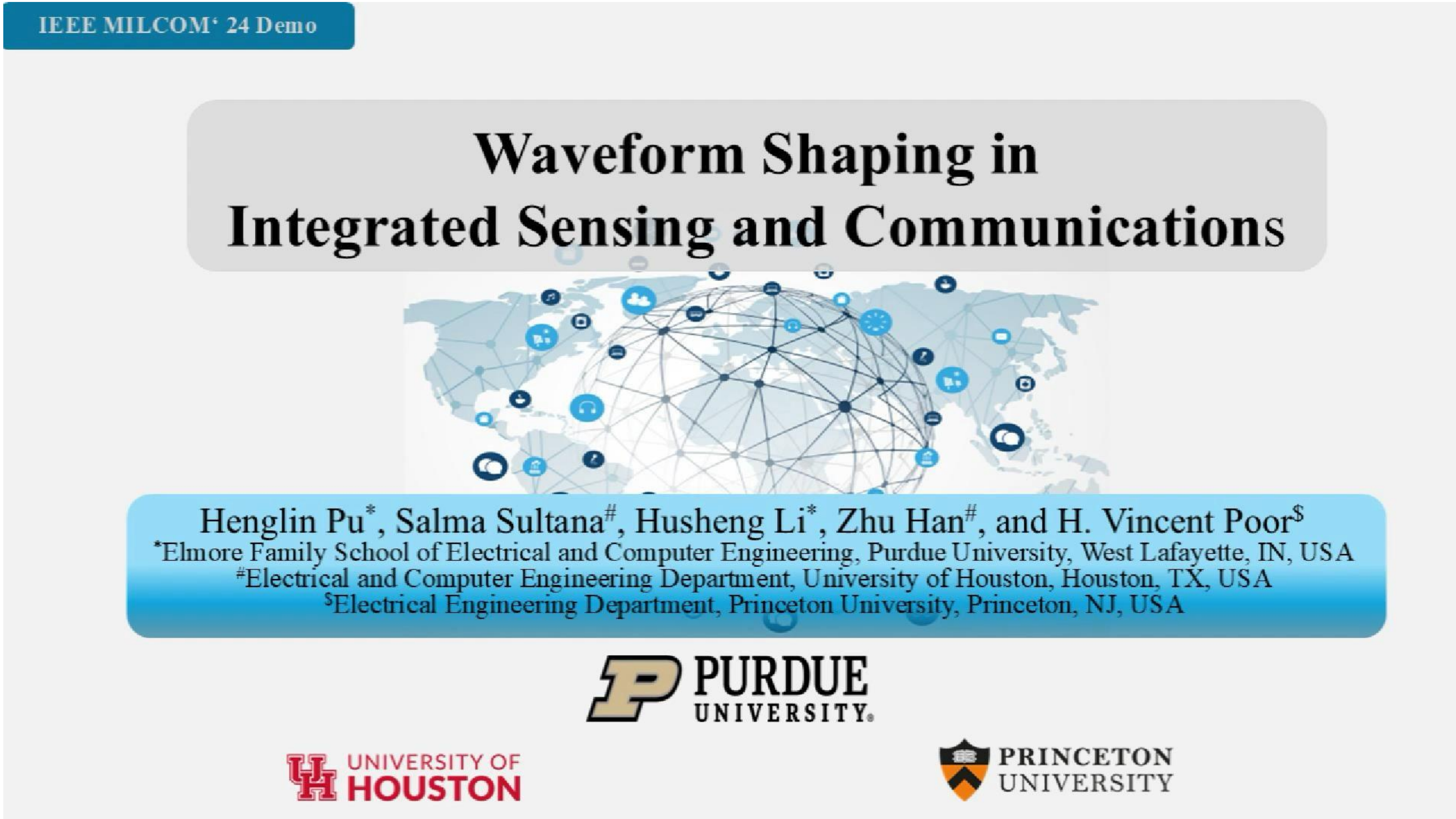


Angle measurement

- Scenario: indoor
- Radar target: metal plate
- Detection range: $[-60°, 60°]$
- Angular accuracy: $15°$



Demo 2: MILCOM 2024



ISAC Timeline and Standardization

1. Early Research and Conceptualization (2020-2023)

- ISAC concept development
- Use case identification
- Initial studies on waveforms (e.g., OTFS, ODDM)

2. Pre-Standardization Phase (2024-2026)

- Development of ISAC performance metrics
- Global trials and collaboration efforts
- 3GPP release 19
- Draft ITU reports for IMT-2030

3. Standardization Preparation (2027-2028)

- Spectrum allocation policies
- Large-scale ISAC trials
- Alignment with global regulations
- Proposal submissions to ITU

4. Formal Standardization (2029-2030)

- ITU's adoption of ISAC in IMT-2030
- ISAC specifications in 3GPP Release 21
- Certification processes for ISAC devices

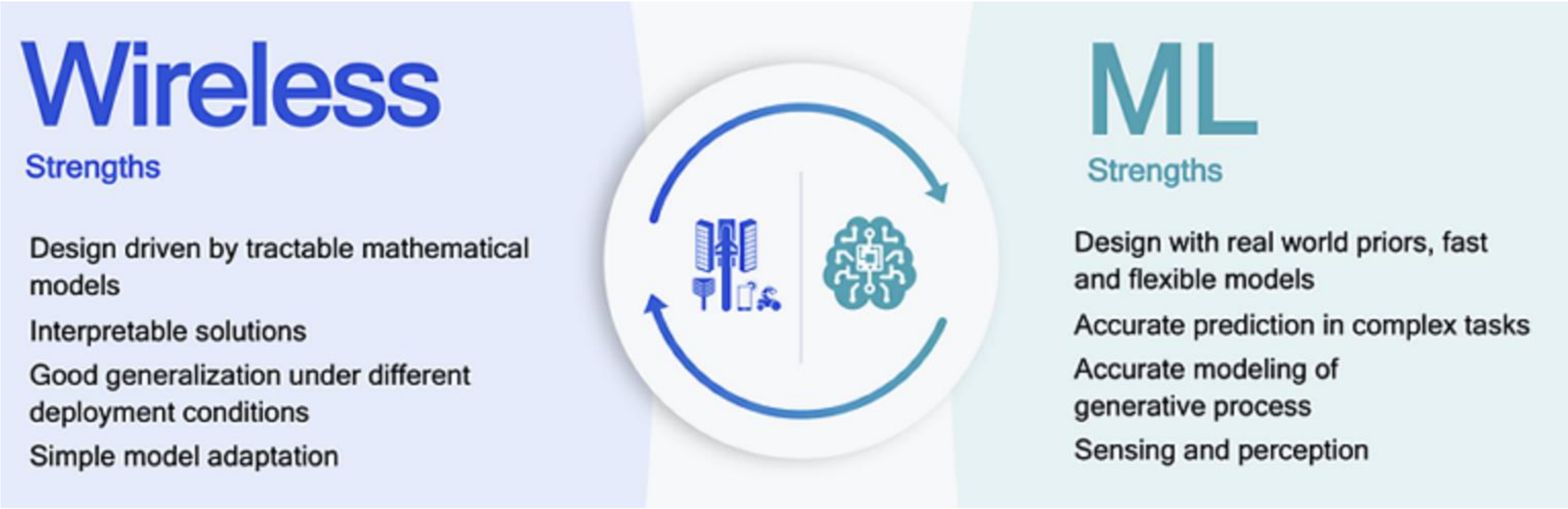
5. Deployment and Global Adoption (2031 and Beyond)

- Commercial rollout of ISAC-enabled 6G networks
- Integration in smart cities, healthcare, and autonomous systems
- Ongoing performance optimization

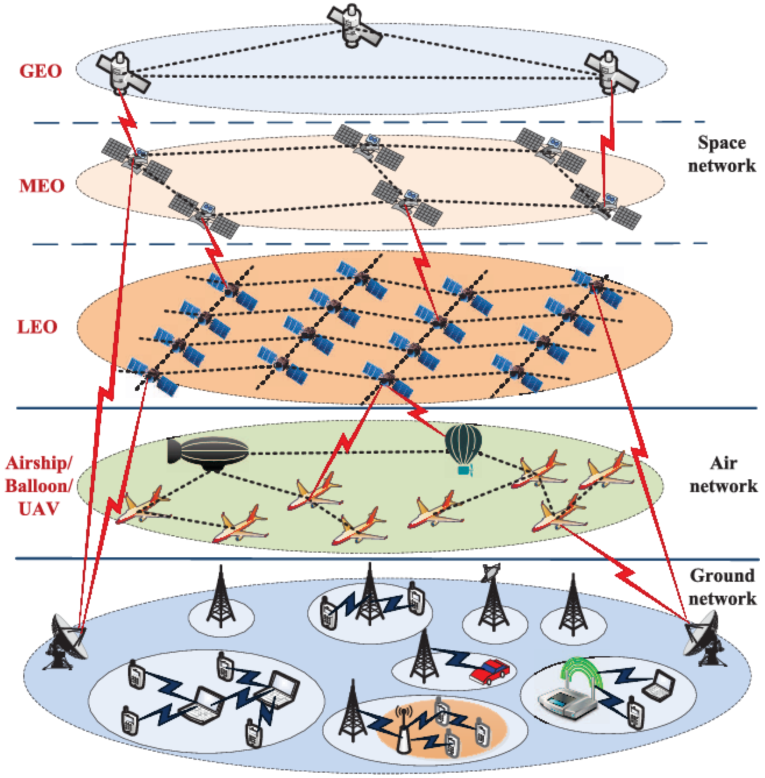
Conclusion and Future Works

- Potential to transform industries and enable a wide array of applications where sensing and communication are tightly integrated, reducing infrastructure complexity and improving efficiency.
- ISAC carefully designs waveforms, beamforming, resource allocation, and hardware to balance these tradeoffs effectively, enabling seamless integration of both functions
- Must find killer applications in industry
- Future works

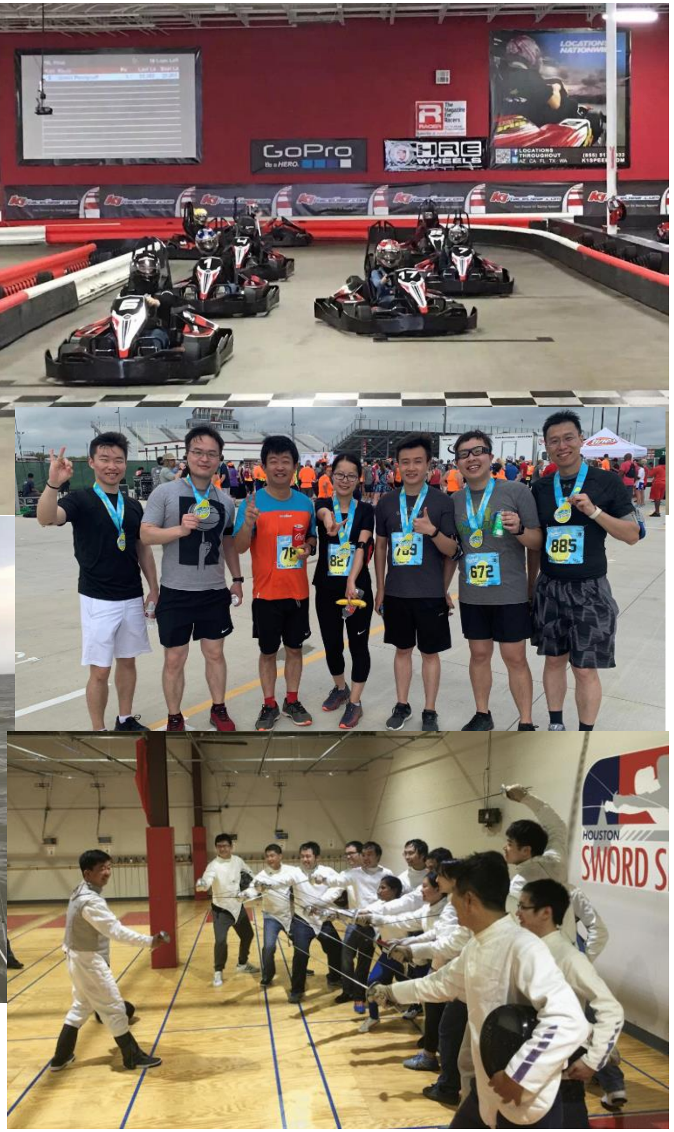
AI for ISAC



SAGIN (DD domain)



Thanks and Welcome to Our Lab



Videos, slides and codes can be found

http://wireless.egr.uh.edu/

http://www2.egr.uh.edu/~zhan2